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Control of Combustion Dynamics by an Electric Field

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An experimental study was conducted by applying a DC electric field to the swirling flame of hydrocarbons with the aim to provide electric control of the gasification/combustion characteristics of biomass (wood pellets). An experimental study of the DC electric field effect on the biomass gasification/combustion characteristics was carried out by varying the bias voltage and polarity of the axially inserted electrode in the range ±0.9 to ±2.7 kV, whereas the ion current was limited to 2 mA. The field effect on biomass gasification was estimated by measuring the field-induced variations of the biomass mass loss rate. The electric field effect on combustion dynamics at thermo chemical conversion of biomass was estimated from complex measurements of the flame velocity, temperature and composition profiles and from calorimetric measurements of cooling water flow. The measurements of the biomass mass loss rate confirm the field-enhanced thermal decomposition of biomass (up to 12-16 %) with field-enhanced mixing of the flame compounds, as well as the improvement of combustion conditions for flaming combustion of volatiles and the radial expansion of the flame reaction zone. The field-enhanced thermal decomposition of biomass and flame homogenization results in increase of the average value of the CO_2 volume fraction in the products by 4-10 % with a correlating decrease of the air excess by 2-6 % in the products as well as in increase of the average temperature values by 2-6 %, whereas the produced heat energy at field-enhanced thermo-chemical conversion of biomass increases by 3-5 % indicating a more complete combustion of volatiles and a more effective heat energy production.

1. Introduction

The electric field effects on the flame flows, which are determined by the electric field-enhanced drift motion of ions and by mass transfer of neutral flame species in the field direction (ion wind) (Payne and Weinberg, 1959) have been investigated for different types of flames (laminar, turbulent) with the aim to control flame stability (Calcote and Berman, 1989) the formation of the flame reaction zone (Colannino, 2012), flame shape, size (Vatazhin et al, 1995) and emission properties (Sakrieh et al, 2005). Systematic studies of the electric field effect on flame stability and emission composition have led to the conclusion that the electric field effect on the flame can be used to improve flame stability limits, it can assure a more complete fuel combustion and to substantially (by about 90%) reduce CO emissions with a relatively low amount of consumed electric power for process control, which does not exceed 0.1 % of the produced thermal power. The electric field effects on the flame flows depend on the electric field configuration and polarity and can be regulated by varying high-voltage DC power supply. A more detailed study of the electric field control of the fuel (propane) combustion downstream the water-cooled combustor shows that the electric field application to the propane flame reaction zone results in field-enhanced processes of interrelated heat/mass transfer to the channel walls and in increase of the produced heat energy. This leads to a correlating decrease of the peak flame temperature and mass fraction of NO_x emission in the products (Zake et al, 2000). Similar field-induced variations of the flame structure, combustion characteristics, heat energy production and composition of polluting emissions were observed, if the electric field was applied to the flame reaction zone developing at thermo chemical conversion of biomass pellets and combustion of volatiles (Barmina et al, 2014). Moreover, these investigations evidence that for the integrated processes of biomass gasification and combustion, the field effect on the combustion characteristics is influenced by the field-enhanced variations of biomass thermal decomposition. Considering

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these observations, the recent study aims to provide a more detailed experimental investigation of the electric field effect on the thermal decomposition of biomass, the formation of the main volatile compounds (CO, H_2 and different fragments of hydrocarbons C_xH_y) and their ignition, and the formation of the flame reaction zone, with a thorough analysis of the field effect on combustion dynamics.

2. Experimental

The electric field effect on combustion dynamics at thermo-chemical conversion of biomass (wood) pellets is studied using a small-scale pilot device composed of a biomass gasifier (1) charged with biomass pellets (240 g) and a water-cooled combustor (5), downstream of which the combustion of the axial flow of volatiles (CO, H_2, C_xH_y) produced at thermal decomposition of biomass develops (Barmina et al, 2014). Diagnostics sections with special openings (6) were used for the measurements of the gasification and combustion characteristics The electric field effect on the thermal decomposition of biomass (wood) pellets and on the combustion of volatiles was studied using an electrode (7), which was axially inserted through the biomass layer, with the top of the electrode located at the bottom of the reaction zone (Figure1).

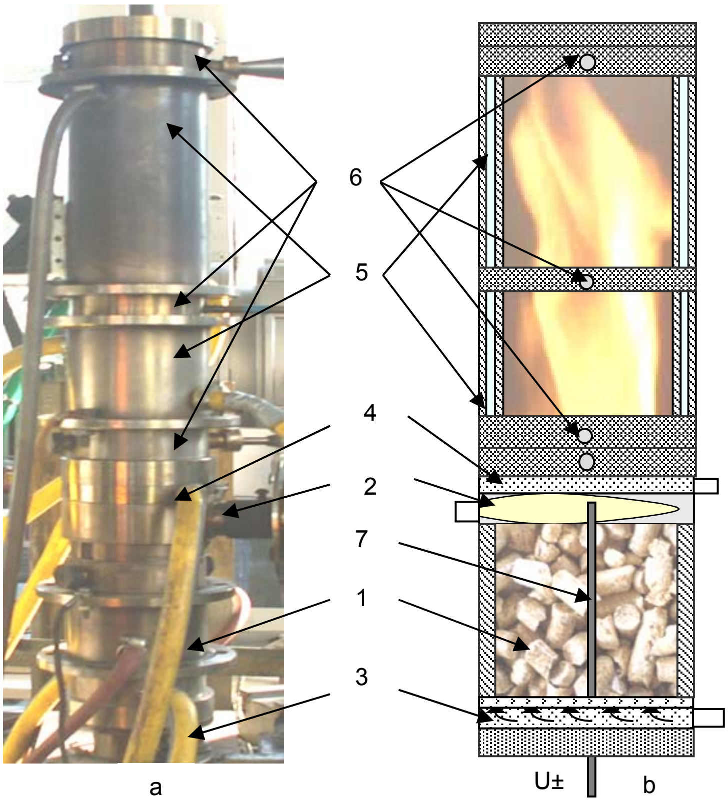

Figure 1: Digital and schematic presentation of the pilot device for experimental study of the electric field effect on thermo-chemical conversion of biomass pellets

The thermal decomposition of biomass was initiated by injecting a propane flame (2) into the upper part of the wood biomass. The primary air (3) at an air excess ratio α ≈ 0.3-0.5 was used to support the process of biomass gasification and the formation of the axial flow of volatiles, and the secondary swirling air supply (4), with a relative low swirl number S < 0.6 determining the formation of air excess in the reaction zone up to α ≈ 1.5-2.0, was used to support the volatiles combustion downstream the combustor.

The experimental study of the electric field effect on thermo-chemical conversion of biomass pellets combines complex measurements of the rate of biomass weight loss using a moving rod with pointer, local spectral measurements of the composition of the produced volatiles close above the wood biomass (L/D ≈ 0.6) using FTIR spectral analysis, local measurements of the flame temperature (L/D ≈ 0.6) using Pt/Pt/Rh thermocouples, local measurements of the flame velocity compounds at the primary stage of the swirling flame formation (L/D ≈ 0.6) using a Pitot tube and a Testo 435 flowmeter, whereas local measurements of the combustion characteristics – combustion efficiency, temperature and composition of the products (volume fraction of CO_2,and O_2 mass fraction of CO, H_2 and NO_x) at L/D = 2.6 were provided with a gas analyzer Testo 350 XL. The time-dependent variations of the temperature and mass flow of the cooling water flow allowed to estimate the heat power variations at different stages of thermo-chemical conversion of biomass and the produced heat energy using a computer date acquisition plate PC-20 TR.

The bias voltage of the electrode relative to the grounded walls of the gasifier and combustor can be varied in the range from U = ±0.6 to U = ±2.4 kV. To restrict the discharge formation, the current in the space between the electrodes is limited to I = 2.5-3 mA.

3. Results and discussion

For the given system configuration with the integrated gasifier and combustor, the thermo-chemical conversion of biomass pellets develops as a complex process of wood biomass decomposition and combustion of the produced volatiles. The thermal decomposition of biomass, developing in the gasifier, is a result of heating, drying and thermal decomposition of hemi cellulose, cellulose and lignin at temperatures 450-650 K, 520-650 K and 520-800 K, respectively, determining the biomass weight loss (Shen et al, 2009). The measurements of the weight loss curves at the thermal decomposition of biomass pellets show that the shape of these curves is typical for the thermal decomposition of ligno-cellulosic material with well demarked regions of the biomass heating, drying, thermal decomposition and char conversion stages (Barmina et al, 2013). The average mass loss rate of biomass pellets at thermo-chemical conversion can vary in the range dm/dt = 0.15-0.16 g/s with the formation of peak value of the weight loss rate (dm/dt = 0.32 g/s) at the primary stage of thermal decomposition of biomass pellets (t ≈ 200-400 s). If the electric field is applied to the biomass layer, the field-enhanced thermal decomposition of biomass pellets results in a sharp increase of the peak value of the biomass weight loss up to dm/dt = 0.4 g/s during the primary stage of biomass decomposition (t = 200-400 s) with a higher average biomass weight loss rate (dm/dt = 0.16-0.18 g/s) during the biomass thermo-chemical conversion (Figure 2-a, b).

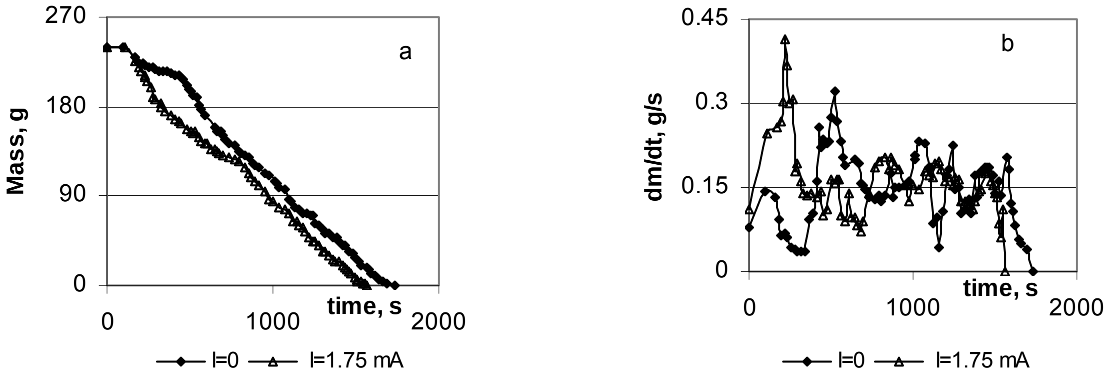

Figure 2: Electric field-induced time-dependent variations of the biomass weight loss (a) and its rates (b)

The field-enhanced increase of the biomass weight loss at the primary stage of biomass heating t > 400 s can be related to electric field-induced activation of the thermal decomposition of hemi cellulose, which starts to decompose at T ≈ 450 K with an intensive release of the volatiles (CO, C_xH_y). This depends on the formation of a field-induced current in the space between the electrodes and determines the formation of the axial flow of the volatiles that is confirmed by the spectral measurements of the absorbance of the main volatile compounds at the bottom of the reaction zone determined by their mass fraction in the flame (L/D ≈ 0.6) (Figure 3-a). It should be noted that the development of endothermic processes during the field-enhanced biomass decomposition results in an intensive consumption of the heat energy produced at partial biomass combustion with limited air supply into the gasifier (α ≈ 0.3-0.5) and needed to support the process of biomass gasification. The calorimetric measurements of the gasifier thermal power confirm that with the constant and limited primary air supply, the biomass field-enhanced thermal decomposition results in a linear decrease of the thermal power released at biomass gasification by about 9.8-13 %, as the field-induced current in the space between the electrodes increases with the correlating decrease of the total amount of the produced heat energy by about 9.5 % during the biomass gasification. The analysis of the energy balance has shown that the development of endothermic processes at the biomass field-enhanced thermal decomposition reduces the gasification efficiency by limiting the rate of biomass gasification and the production of volatiles, hence, determining the formation of gasification instability. Therefore, by increasing the field-induced current in the space between the electrodes, the absorbance of the produced volatiles tends to increase to a peak value at I ≈ 1.5 mA, with a slight decrease at the higher values of the field-induced current (Figure 3-a). Note that the field-enhanced heat energy consumption advances the decrease of the peak flame temperature at the primary stage of biomass thermal decomposition (t = 400 s) (Figure 3-b) thus decreasing the average temperature at the bottom of the reaction zone (Figure 3-b) with the correlating field-induced variations of the flame dynamics decreasing the average value of the axial flow velocity by about 20 %.

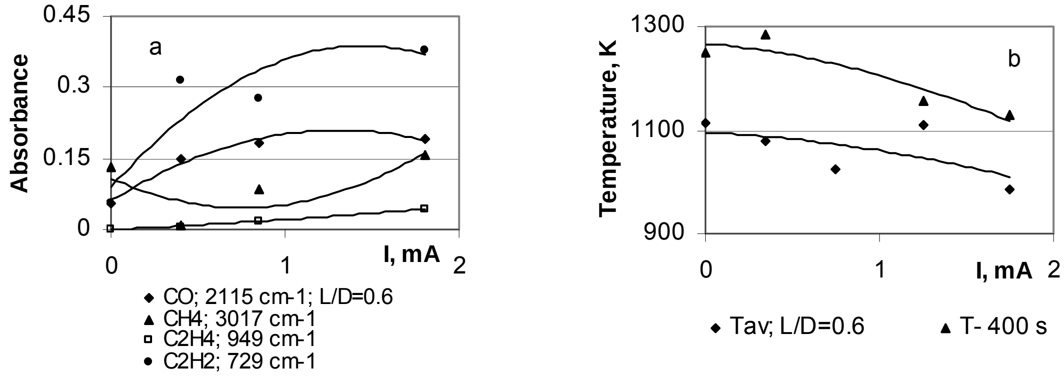

Figure 3: The electric field-induced variations of the absorbance and composition of volatiles (a) peak and average flame temperatures (b)

The field-enhanced biomass thermal decomposition with the field-enhanced formation of volatiles shows its direct influence on the development of combustion dynamics downstream the combustor. With the air excess supply to the bottom part of the reaction zone (α ≈ 1.4), a dominant feature of the field-enhanced biomass thermal degradation is the faster ignition and burnout of volatiles with higher peak values of the volume fraction of the main product (CO_2), flame temperature and thermal power released at the flaming stage of volatiles combustion (t = 400-1000 s) (Figure 4a-c). The total amount of the produced heat energy downstream the flame reaction zone increases by about 3-5.5 % with the average field-enhanced decrease of the gasifier thermal power by about 13 % (Figure 4-d) and correlating decrease of the air excess ratio from 0.42 to 0.3 at the biomass gasification stage.

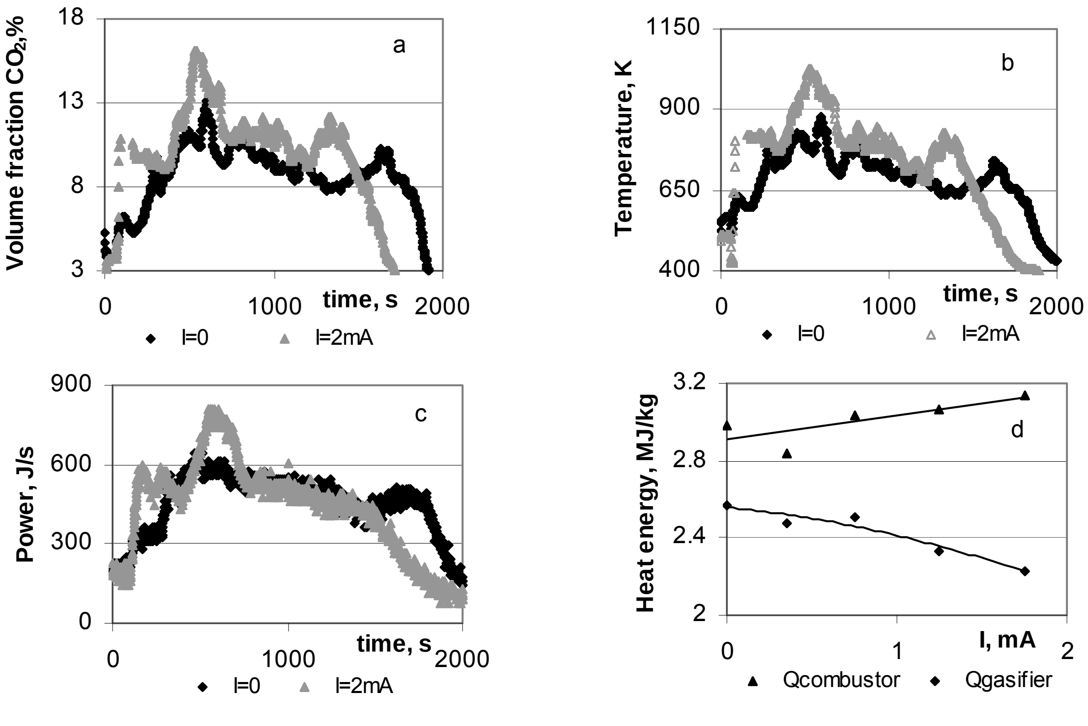

Figure 4: Electric field-induced time-dependent variations of the flame composition (a), temperature (b), heat power (c) and produced heat energy (d) at biomass thermal decomposition

The local measurements of the flame composition and temperature in the flame reaction zone (L/D = 2.6) showed that, in an addition to the biomass field-enhanced thermal decomposition resulting in the faster ignition and enhanced burnout of volatiles, the ion wind effect on the formation of the flame reaction zone must be taken into account. Under conditions, when the combustion of volatiles develops at a nearly constant average temperature and heat energy release (t > 1000-1500 s), the field-enhanced radial expansion of the flame reaction zone (L/D = 2.6) is observed (Figure 5, a-d). The local measurements of the flame temperature and composition confirm that the radial expansion of the flame reaction zone can be related to the field-enhanced radial mass transfer of the flame species (ion wind effect), along with the field-enhanced mixing of the axial flow of volatiles with the swirling air along the airside part of the reaction zone. As a result of the field-enhanced mixing of the flame compounds, the local increase of the CO_2 volume fraction, flame temperature and combustion efficiency along the outside part of the reaction zone is observed, with the correlating decrease of the air excess in the products indicating improvement of the combustion conditions during the biomass field-enhanced thermal decomposition. In addition, the field-induced decrease of the average values of the CO mass fraction from 700 to 230 ppm and NO_x mass fraction from 48 ppm to 39 ppm confirms a cleaner and more effective heat energy production under the electric field effect on the flame reaction zone.

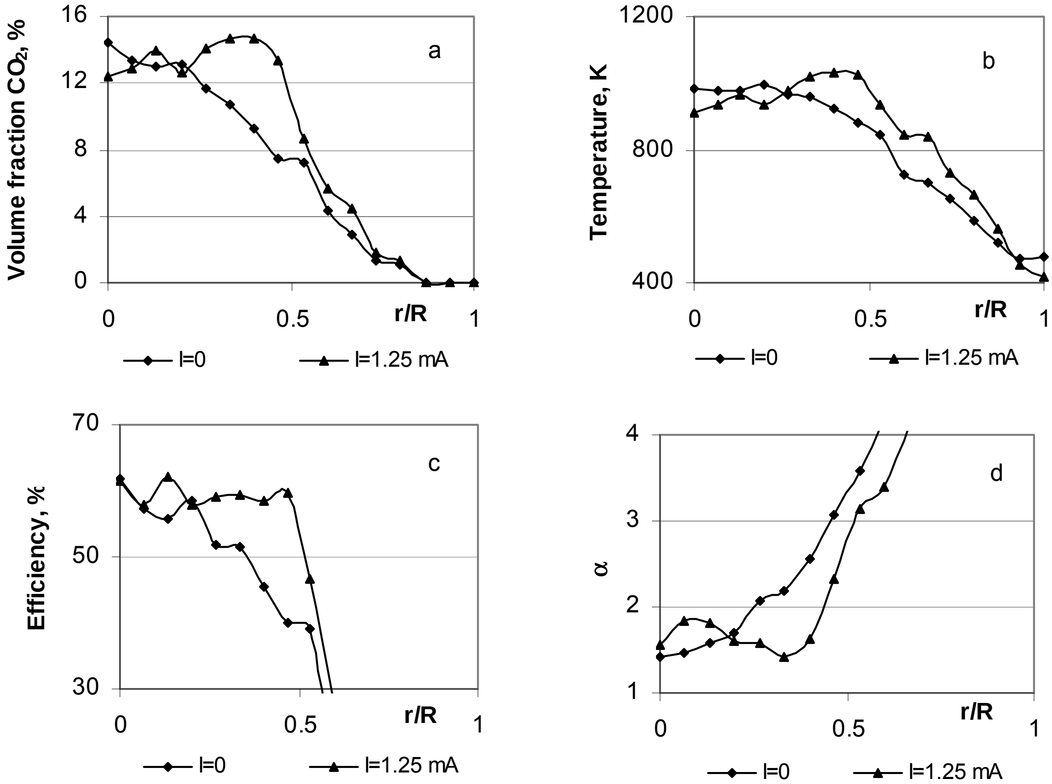

Figure 5: Field-induced variations of the radial distribution of the flame composition (a), temperature (b), combustion efficiency (b) and air excess ratio in the reaction zone (L/D = 2.6)

4. Conclusions

From the results of the complex experimental study of the DC electric field effect on the main combustion characteristics at thermo chemical conversion of biomass pellets the following conclusions can be drawn.

Under conditions, when the positively biased electrode is inserted through the biomass layer, with the top of the electrode at the bottom of the reaction zone, the resulting electric field effect on the combustion characteristics is determined by two main factors: the field-enhanced biomass thermal decomposition determining the field-enhanced formation of the axial flow of volatiles, and the field-enhanced interrelated processes of radial heat/mass transfer of the flame species along with field-enhanced mixing of the flame compounds and radial expansion of the reaction zone.

The field-enhanced biomass thermal decomposition results in a faster ignition and burnout of the volatiles during the flaming stage, whereas the field-enhanced mixing of the flame compounds provides a more complete combustion with an increase in combustion efficiency and decrease in average values of polluting

emission (CO, NO_x) in the products, confirming a cleaner and more effective heat energy production under the DC electric field effect on the flame.
Under the limited air supply and fuel-rich conditions in the gasifier, the field-enhanced endothermic process of biomass gasification results in field-enhanced heat energy consumption thus decreasing the heat power released at biomass gasification that is used to support the biomass gasification by limiting the rate of volatiles' production and reducing the electric field effect on the combustion dynamics. The process in overall requires an optimization in synchronizing both the field-enhanced biomass gasification and the field-enhanced biomass combustion processes.

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