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Electric Field Effects on the Combustion Characteristics of Renewable Fuel

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Abstract

Active electric control of combustion dynamics at different stages of wood fuel burnout have been investigated experimentally, using a small scale pilot device, the main elements of which are a wood fuel gasifier and a combustor with swirl-enhanced mixing of flame compounds and combustion of volatiles. The electric field (DC, AC) effect on wood fuel gasification and combustion of volatiles downstream the combustor is studied experimentally for the regimes of field-enhanced mass transfer (ionic wind effect) and corona torch discharge using a flame-attached electric field. Variations of strongly swirled flame response to the applied electric field, combustion characteristics and combustion efficiency under conditions of DC and high-frequency AC electric field are detected and analyzed with approbation of the field effects on the flame characteristics for a domestic heating furnace.

Introduction

Combustion control and enhancement by applying external DC and AC electric fields, as well as using different types of discharges have been widely studied since 1960 with the aim to improve and stabilize combustion characteristics [1-5]. All these studies confirm improvement of the combustion characteristics at a relative low energy consumption if compare with thermal load of flames. The results of experimental research [1-3] and numerical modelling [4, 5] of the electric field effects on the flame characteristics make it possible to conclude that the field-enhanced modification of the flame dynamics and combustion characteristics, when a low voltage DC electric field ($U < 3$ kV) is applied to the flame reaction zone, can be related to a field-enhanced drift motion of positive flame ions (CHO^+, H_3O^+, $C_2H_2^+$, etc) with momentum transfer to neutral flame species during elastic collisions, while collisions (elastic, inelastic) between the electrons and neutrals are inefficient and can be neglected. Inelastic collisions between electrons and neutral flame species with enhanced excitement, dissociation and ionization of the main flame compounds start to compete with a field-enhanced energy exchange between ions and neutrals by increasing the applied voltage and energy of free electrons with gradual transition to the regime of corona discharge [2, 6, 7]. In consequence, the corona discharge region can be defined as a region, where corona-discharge enhanced chemical reactions, determining the variations of the combustion conditions, can occur. Because of the pronounced DC and AC corona discharge effects on different types of flames, the detailed research of field effects on the combustion characteristics is still interesting including its theoretical and practical importance. Previous investigations demonstrate that the electric control of the swirling propane flame flow dynamics at low applied DC voltage allows control the flame carbon and the formation of the flame shape and size [3]. The recent experimental study is aimed at reviewing the field effects on the combustion characteristics of renewable fuel (wood pellets) under conditions of electric field-enhanced ion drift motion and plasma-assisted corona discharge in a strongly swirled flame flow, providing approbation of the research results in the furnace of a domestic heating system with the aim to develop a practically useful technique, which would provide additional control of the wood fuel gasification and combustion of volatiles.

1. Experimental Set-up

First, the electric field effect on the wood fuel gasification and combustion of volatiles is studied experimentally, when the processes of electric field-enhanced heat/mass transfer (ion wind) controls the strongly swirled flow dynamics ($\boldsymbol{S} = 2/3v_{tg}/v_{ax} > 1$). The pilot device for such research is composed of a wood fuel gasifier and a water-cooled combustor with an axially inserted 250 mm long electrode, with the electrode tip being close to the bottom part of the swirling flame flow ($L/D \approx 1$) (Fig. 1a). To restrict the formation of corona discharge, the bias voltage of the axially inserted electrode is limited to $U = \pm 3$ kV, while the ion current in the flame is limited to 1 mA.

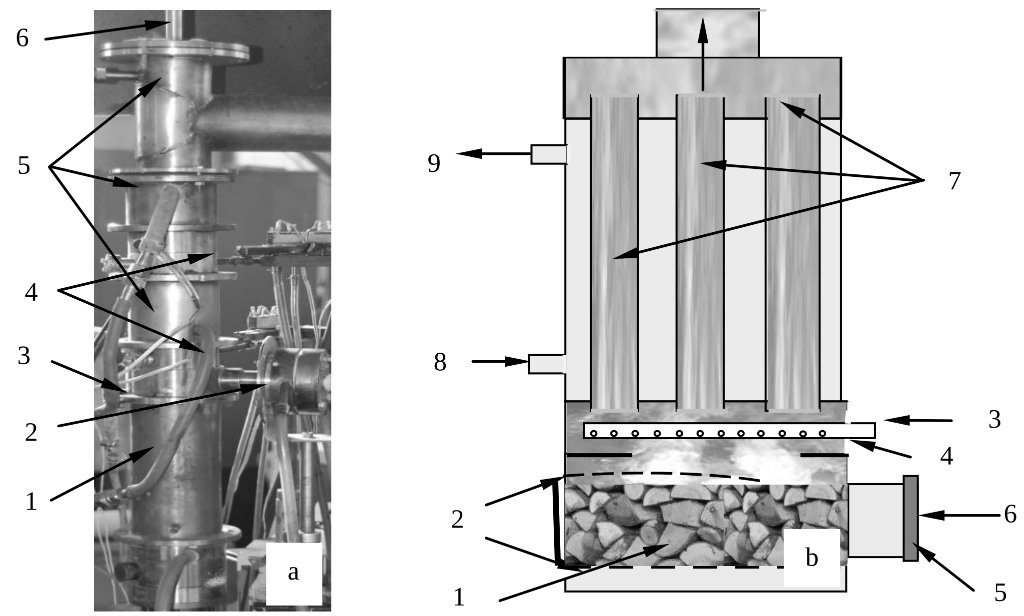


Fig. 1. a – digital image of the pilot device: 1 - gasifier, 2 – propane burner, 3 - secondary swirled air supply above the wood layer, 4 - sections with peepholes for thermocouples and gas sampling probe, 5 - water-cooled channel sections, 6 - axially inserted electrode;
b – domestic heating boiler: 1 - furnace, 2 – background air choke, 3 – propane injector, 4 – propane air, 5 – ionizer, 6 – activated airflow, 7- flue gas system, 8, 9 - water inlet and outlet

In addition to the field-enhanced ionic wind effect on the combustion characteristics of the wood fuel, an experimental study of the field effect on the swirl flame formation and combustion characteristics is carried out under conditions, when the corona torch discharge is initiated between the tip of the axially inserted electrode and the grounded water-cooled walls of the combustor. Under conditions of AC corona discharge activated combustion, the AC field effect on the combustion characteristics is studied experimentally using the fixed frequency 41 MHz and restricting the discharge power to ~10% of the thermal load of the flame reaction zone. Finally, the field effect on the combustion characteristics is studied under conditions of DC corona-discharge activated air supply into the furnace of a domestic heating system (Fig. 1b). The bias voltage of the electrode for the corona discharge approaches U = 14 kV at a discharge current of 0.8-1 mA, while the field intensity is close to 6 kV/cm.

The electric field effect on the combustion characteristics is estimated by measuring the flame composition at different stages of the flame formation by varying the applied power and bias voltage of the axially inserted electrode. The measurements are made by a Pitot tube and a gas analyzer Testo-350XL. The electric field effect on the flame temperature is investigated using Pt/Pt-Rh thermocouples and a data recording system PC-20TR.

2. Results and Discussion

2.1. Electric Field-induced Ionic Wind Effect on the Combustion Characteristics

With the given design of the pilot device (Fig. 1a), the dominant feature of the undisturbed swirling flame flow (U = 0) is the formation of a low-temperature staged combustion of volatiles downstream the combustor with a swirl-induced recirculation close to the outlet of the gasifier. When a relative low voltage (U < 3 kV) DC electric field is applied to the swirling flame flow, field-enhanced variations of the swirl flow dynamics and structure of the flame recirculation zone are observed. A more pronounced electric field effect on the recirculation with direct impact on the wood fuel gasification and combustion of volatiles is detected for positive bias voltage of the axially inserted electrode, when the electric force repels positive flame ions from the axially inserted electrode and enhances the reverse axial heat/mass transfer to the wood layer with a more intensive wood fuel gasification and correlating increase of the mass fraction of main volatiles (CO, H_2) in the flame reaction zone (Fig. 2).

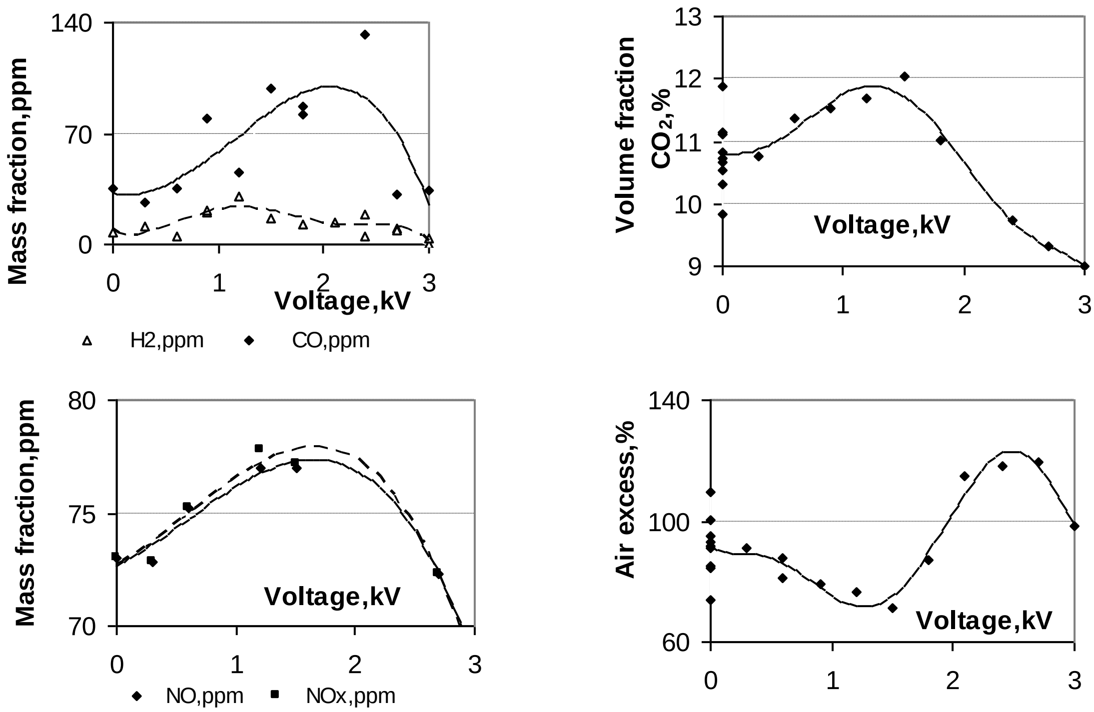


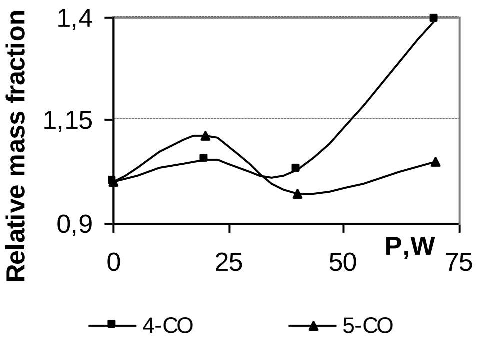
Fig. 2. Net electric field effect on the wood fuel gasification and composition of the flame reaction zone

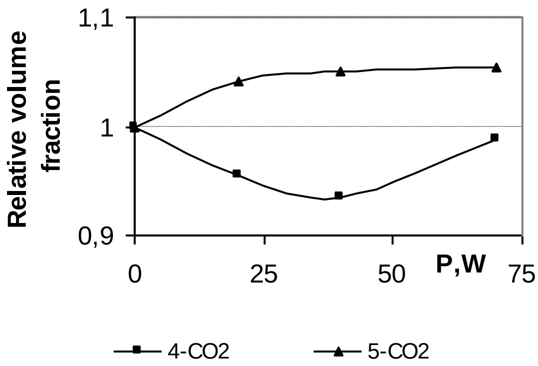
Moreover, the field-enhanced recirculation promotes an enhanced mixing of the flame compounds close to the flame base with an enhanced combustion of the volatiles downstream the combustor. As it follows from Fig. 2, the peak electric field effect on the combustion characteristics is observed at moderates values of DC voltage, ranging U = 1.2-1.5 kV. At a higher bias voltage, the mass fraction of the main products in the flame reaction zone, flame temperature and the combustion efficiency start to decrease, while increases the air excess in the products, indicating that the competitive process of the field-enhanced radial heat/mass transfer to the water-cooled channel walls promotes the flame extinction.

In summary, the field-induced variations of the swirl flow dynamics and composition of the products at the field-enhanced ion wind formation confirm that the field-enhanced reverse axial heat/mass transfer at moderate applied voltages (U < 1.5 kV) can be used to control the wood fuel gasification and combustion of volatiles, making them more effective.

2.2. Effect of Corona Discharge on the Combustion Characteristics of Wood Fuel

When a high-frequency AC field is applied to the flame base, resonant AC field oscillations initiate the AC torch discharge at the electrode tip, providing variations of the combustion characteristics of the swirling flame flow. For the typical combustion conditions of atmospheric pressure swirling flame flow, when the average heat power during wood fuel burnout is about 800-1000 W, the thermal effect of the corona torch discharge on the combustion efficiency and temperature of the products is quite negligible (<1%) with a more significant impact of the AC discharge on the composition of the products (Fig. 3).





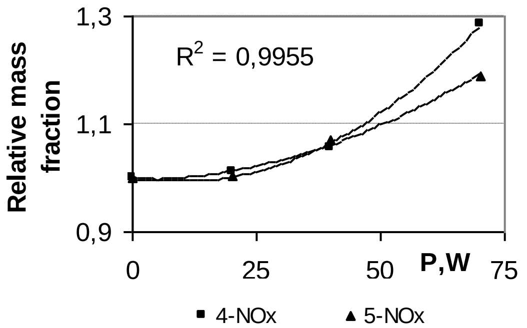


Fig. 3. Effect of the AC torch discharge on relative variations of the product composition at different stages of wood fuel burnout (4 - 760-880 s; 5 -880-1000 s)

The AC field-induced variations of the product composition at a nearly constant temperature of the products (Fig. 3) allow to suggest that the dominant effect of the AC torch discharge on the combustion characteristics at the low-temperature staged combustion downstream the combustor (T = 1300-1400 K) can be related to the field-enhanced excitement and dissociation of the flame compounds, predominately, free oxygen, promoting reactions between atomic oxygen and neutral flame species such as:

$$O+CO_2 \leftrightarrow O_2+CO; \quad (1)$$

$$O+N_2 \leftrightarrow NO+N;$$

$$N+O_2 \leftrightarrow NO+O. \quad (2)$$

The field-enhanced variations of the flame composition confirm that increasing the power of the AC discharge applied to the swirling flame base disturbs a balance between the reactions of CO_2 formation and destruction (1) with correlating variations of the mass fraction of CO and air excess in the products. As it follows from Fig. 3, at the AC torch discharge, the balance between the field-enhanced formation/destruction of CO_2 during the burnout of volatiles is quite unstable, and the more intensive field-induced oscillations of CO formation occurs when the temperature of the flame reaction zone approaches a peak value $T \approx 1300$-1400 K (t = 760-880 s), and it is quite negligible at the end stage of the wood fuel burnout (T = 880-1000 s) when the temperature of the reaction zone decreases below 1300 K. In addition, the enhanced dissociation of free oxygen by increasing the AC discharge power promotes the formation of NO_x via Zeldovich mechanism (2), increasing the mass fraction of NO_x in the products. In fact, the relative contribution of the corona torch discharge to the formation of NO and CO may become significant and achieves 30-40% at relative low and acceptable total values of the NO and CO mass fraction in the products (<100 ppm) when the strongly swirled secondary airflow promotes the low-temperature staged combustion of the volatiles.

Finally, note a very interesting and promising fact that the pronounced effect of the corona discharge on the wood fuel gasification and combustion of volatiles with a correlating increase of the product temperature and produced heat power in the furnace can be obtained if the corona discharge is initiated at the nozzle for air supply into the furnace (Fig. 4). As it follows from Fig. 4, for the given conditions, the effect of the corona discharge on the wood fuel gasification and combustion of volatiles is comparable with the effect of propane co-fire, determining the enhanced wood fuel gasification and ignition of volatiles at the initial stage of the flame formation (t < 10 min) and can be used to assure the effective combustion control of the wood fuel in the furnace without additional tools (electrodes, nozzle for propane supply, etc.) in the active combustion zone of wood fuel.

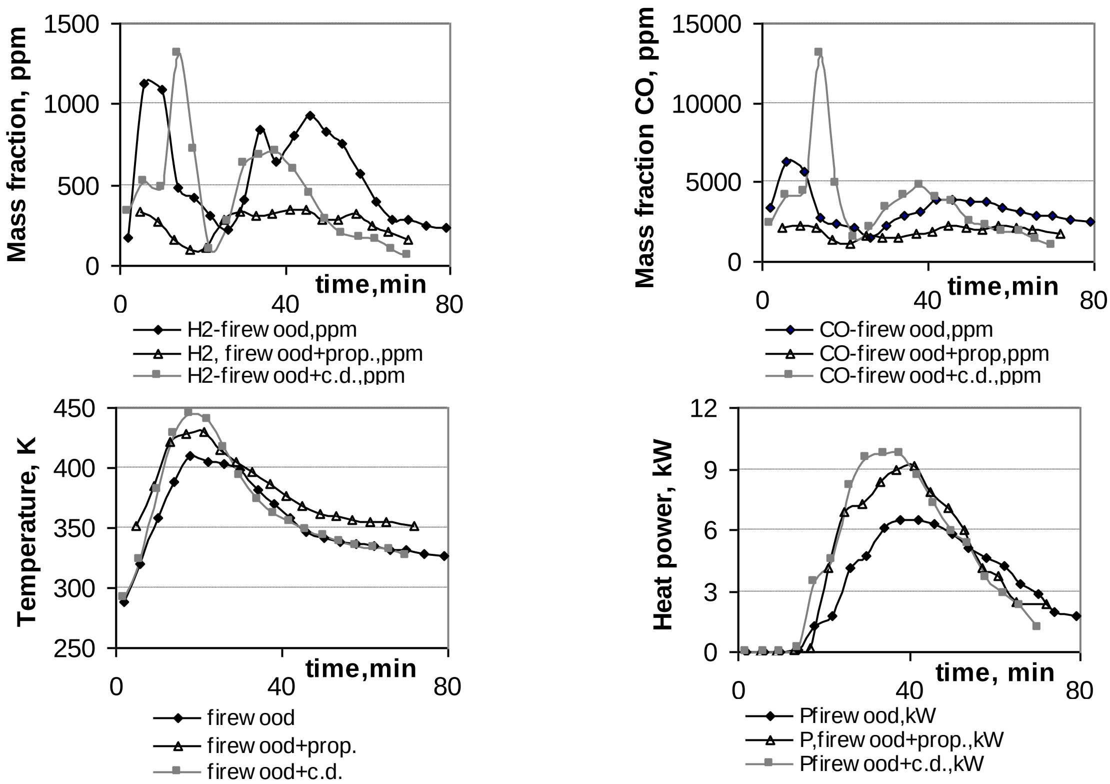


Fig. 4. Corona discharge effect on the wood fuel gasification, temperature of products and heat power in a furnace of domestic heating

Conclusions

The electric field effect on the flame formation and wood fuel combustion is studied experimentally both under conditions of field-induced mass transfer (ionic wind) ($U < 3$ kV) and corona discharge, determining the variations of the combustion dynamics and composition of emissions with direct influence on the combustion efficiency and produced heat power.

Under conditions of field-enhanced mass transfer in a field direction ($U < 3$ kV), the most pronounced electric field effect on the combustion characteristics and composition of the products is observed at the positive bias voltage of the central electrode, when the field-enhanced reverse axial heat/mass transfer supports the enhanced wood fuel heating and gasification by increasing the combustion efficiency of volatiles.

Under conditions of AC corona torch discharge activated combustion, the enhanced dissociation of free oxygen disturbs the balance between the formation and destruction of CO_2, promoting a field-enhanced formation of CO during the burnout of volatiles and a field-enhanced formation of NO_x emissions at relative low and acceptable total values of the NO and CO mass fraction in the products (<100 ppm).

A more pronounced effect of the corona discharge on the wood fuel gasification and combustion of volatiles with a correlating increase of the product temperature and produced heat power in the furnace can be obtained if the corona discharge is initiated at the nozzle for air supply into the furnace. With the given conditions, the effect of the field-enhanced combustion of volatiles is comparable with the effect of propane co-fire on the wood fuel burnout, indicating that the corona discharge can be used as a promising tool to control combustion.

References

[1] Lawton, J.and Weinberg, F.J.: *Electric Aspects of Combustion*. Clarendon Press, Oxford, 1969, pp. 95-130.

[2] Dunn-Rankin, D.: *Characterization of Ionic Winds from Flames and Corona Discharges*. GALCIT Fluid Mechanics Seminar, Academic Year 2005, UC Irvin.

[3] Zake, M., Barmina, I., Turlajs, D., Lubane, M., Krumina, A.: *Swirling Flame. Part 2. Electric Field Effect on the Soot Formation and Greenhouse Emissions*. Magnetohydrodynamics, Vol. 40, 2004, No. 2, pp. 183-202.

[4] Belhi, M., Domingo, P., Vervisch, P.: *Effect of Electric Field on Flame Stability*. Proceedings of the European Combustion Meeting, 2009, pp. 1-6.

[5] Mitra, S., Sharma, P., Godbole, M., Kumar K. M.: *Analyzing the Influence of Electric Field on Flame through Electrodynamics*. COMSOL Conference, Bangalore, 2009.

[6] Koshy Panicker P.: *Ionization of Air by Corona Discharge*. Thesis Master of Sci. in Aerospace Engineering, University of Texas at Arlington, 2003, pp.102.

[7] Chen, J., Davidson , J. H.: *Model of the Negative DC Corona Plasma: Comparison to the Positive DC Corona Plasma, Plasma Chemistry and Plasma Processing.* Vol. 23, No.1, 2003, pp. 83-90.

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