ELECTRIC FIELD EFFECT ON BIOMASS COMBUSTION CHARACTERISTICS

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Abstract. The main aim of the present study is to obtain clean and effective heat energy production by applying a DC electric field to the flame reaction zone and providing control of the processes developing at thermochemical conversion of biomass (wood) pellets. The average heat power of the experimental device with continuous supply of pellets at an average supply rate of 1.1-2 $g \cdot s^{-1}$ and optimized flame structure is ~20 kW. The electric field effect on combustion characteristics is estimated from field-induced variations of the flame temperature, composition and combustion efficiency by varying the applied voltage and ion current between the electrodes. The mechanism of field-enhanced variations of the combustion characteristics is analyzed with account of the field-induced ion wind effects on the biomass thermal decomposition and on the formation of the flame reaction zone.

Keywords: biomass, electric field, ion wind, combustion characteristics.

Introduction

Electric-field control of the combustion characteristics has been an interesting research subject with theoretical interest and promising practical applications to improve and stabilize the industrial processes in burners, boilers, furnaces and engines [1-7]. Theoretical research into this field focuses on an electrodynamic flame response to an electric field with account of electric body force-induced ion wind effects [1-5] and plasma assisted combustion [6; 7]. In accordance with the Navier-Stokes equation system, the main steps of electric field-induced variations of the combustion characteristics due to the ion wind effect combine, first, a contribution of the electric force ($F = q_{\pm}n_{\pm}E$) to the momentum equation with field-induced variations of the flame dynamics, a contribution to the mass transport of flame species with local variations of the flame composition and, finally, a contribution to the energy transport with local variations of the combustion chemistry and flame temperature [8]. The detailed experimental research of the flame response to the electric field confirms that the electric field-induced ionic wind motion, which depends on the density of the charged flame species (n_i^+, n_i^-), ensures effective control of the flame velocity profiles and processes of heat/mass transfer, resulting in local variations of the flame temperature and composition profiles, combustion efficiency and heat energy production, providing a cleaner and more effective heat energy production both for flames of gaseous fuels and at thermochemical conversion of biomass [5; 9-12]. In fact, the flame shape and size can be significantly affected at a relatively low electric power, less than 0.1 % of the produced heat power at thermochemical conversion of biomass with a substantial reduction in CO, particulate material, nitrogen oxides and in uncombusted organic material for all types of combustion systems, such as small stoves, fireplaces, smelting furnaces, boilers, etc. [13]. It has been shown that the flame response to the electric field is influenced by many factors, such as the flame ionization degree, the field and flame configuration, the design of the electrode, the applied voltage and polarity, the type of fuels, the number and location of electrodes in the flame [13-16]. Numerous experiments with different configurations of electrodes were conducted to optimize the DC and AC electric field effect on the flame and combustion characteristics using a single electrode configuration, as well a sequence of electrodes, which were located in the combustion volume [17]. The preferable strength of the electric field in the flame reaction zone between the electrodes is between 0.2 and 1 $kV \cdot cm^{-1}$ [13].

A previous experimental study of the electric field effect on the combustion characteristics at thermochemical conversion of biomass (wood pellets) was carried out using a batch-size experimental device with integrated processes of biomass gasification and combustion of volatiles with an average heat power of 2-3 kW. The goal of the present study was to investigate the DC electric field effect on the thermochemical conversion of biomass pellets using continuous supply of pellets onto the bottom of the combustor, with the single electrode configuration. The electric field-induced variations of the flame composition, temperature and combustion efficiency were tested and discussed considering the electric field effect on the combustion stability.

Experimental

The experiments were performed using a quartz tube combustor (1) of length $L = 1000$ mm and of diameter $D = 120$ mm. Figure 1 shows schematically the cross-section of the combustor, the electrode arrangement and the electric circuit. To prevent the formation of discharge, a resistor of $R = 500$ kΩ was used to limit the current between the electrodes to $I = 10$ mA. The bias voltage up to 3 kV was applied between the positively biased nichrome electrode (6) of 5 mm in diameter, which was axially inserted at the distance $L = 90$ mm above the bottom of the combustor and at $L \approx 60$ mm above the surface of the wood pellets layer (2). A ring-shaped grounded electrode (7) was located at the bottom of the quartz burner, above a mesh, which served as a base to support the layer of biomass pellets (8). The continuous supply of wood pellets (3) onto the mesh was provided at the average rate 1-1.3 $g \cdot s^{-1}$ using the secondary air flow (5) with the average air supply rate 300 $l \cdot min^{-1}$. The gasification of wood pellets was supported by the primary air supply (4) below the layer of wood pellets at the average rate 300 $l \cdot min^{-1}$.

Complex measurements of the combustion characteristics combine online measurements of the volume fraction of CO_2, mass fraction of CO, H_2, NO_x, air excess, flame temperature and of the combustion efficiency. These measurements were made using a gas analyzer Testo 350 XL and a gas sampling probe (9), which was placed in the flame just above the combustor. The electric field effect on the combustion characteristics was studied by measuring the combustion characteristics by varying the positive bias voltage of the axially inserted electrode (6) from 0 up to +3 kV with a correlating variation of the current in the flame space between the electrodes from 0 up to 6 mA.

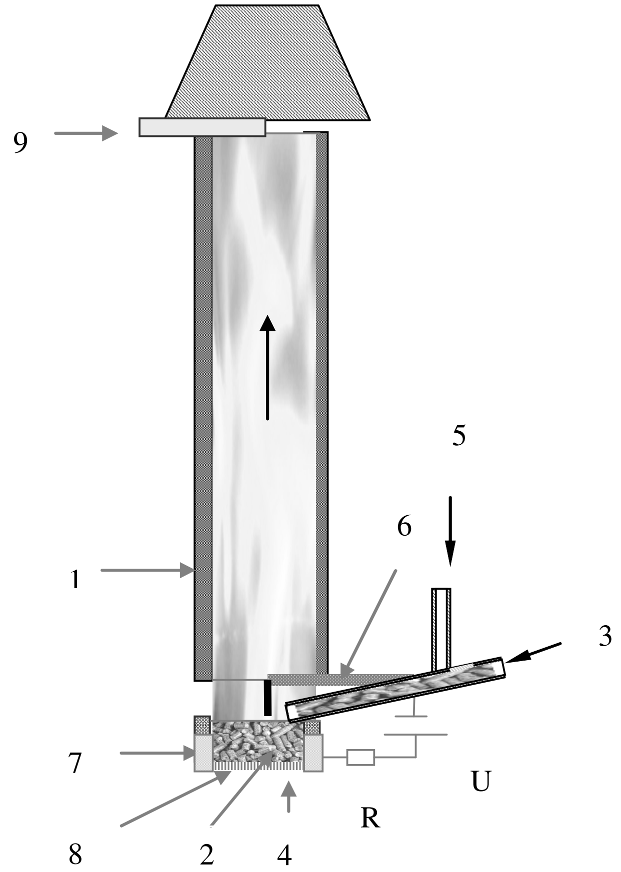

Fig. 1. **Schematic cross-sectional view of the combustor and electrode arrangement:** 1 – quartz tube combustor; 2 – wood layer; 3 – supply of wood pellets; 4 – primary air supply; 5 – secondary air supply; 6 – nichrome electrode; 7 – ring shaped grounded electrode; 8 – mesh; 9 – gas sampling probe

In all experiments, the biomass (wood pellets) thermochemical conversion was carried out in the regime of turbulent flow with the air excess in the flame reaction zone determining the variation of the air equivalence ratio (α) in the 1.6-2.5 range. The regression analysis of the average values of flame parameters (temperature, composition, etc.) during the fixed time interval of the process development (400 s) for the experiment quote (up to 5) was carried out to estimate the process stability and verify the electric field effect on biomass combustion characteristics. The regression analysis of the process stability has shown that deviation of the main flame characteristics (temperature, volume fraction of CO, CO_2, air excess, etc.) from the average values for the experiment quote does not exceed 4-4.6 %, and is relatively small comparing to the electric field-induced variation of the combustion characteristics, as it follows from the results of the experimental study presented below.

Results and discussion

With the given electrode arrangement and limited ion current between the electrodes (Fig. 1), the DC electric field effect on the combustion characteristics is a result of the field-enhanced formation of electrodynamic flows, when a collisional transfer of momentum from the accelerated charged species to the neutrals results in a field-enhanced ion wind motion in the field direction, i.e., from the flame reaction zone up to the surface of the biomass layer. At the primary stage of biomass thermal decomposition ($t < 100$ s), the density of the charged flame species (CHO^+, $C_3H_3^+$, H_3O^+) at the bottom of the combustor is low, which is confirmed by the high electrical resistance in the space between the electrodes (~MΩ) by limiting the formation of the ion current and ionic wind motion in the field direction. At this stage of flame formation, the electric field-enhanced biomass thermal decomposition correlates with the field-enhanced release of the volatiles (CO) (Fig. 2-a).

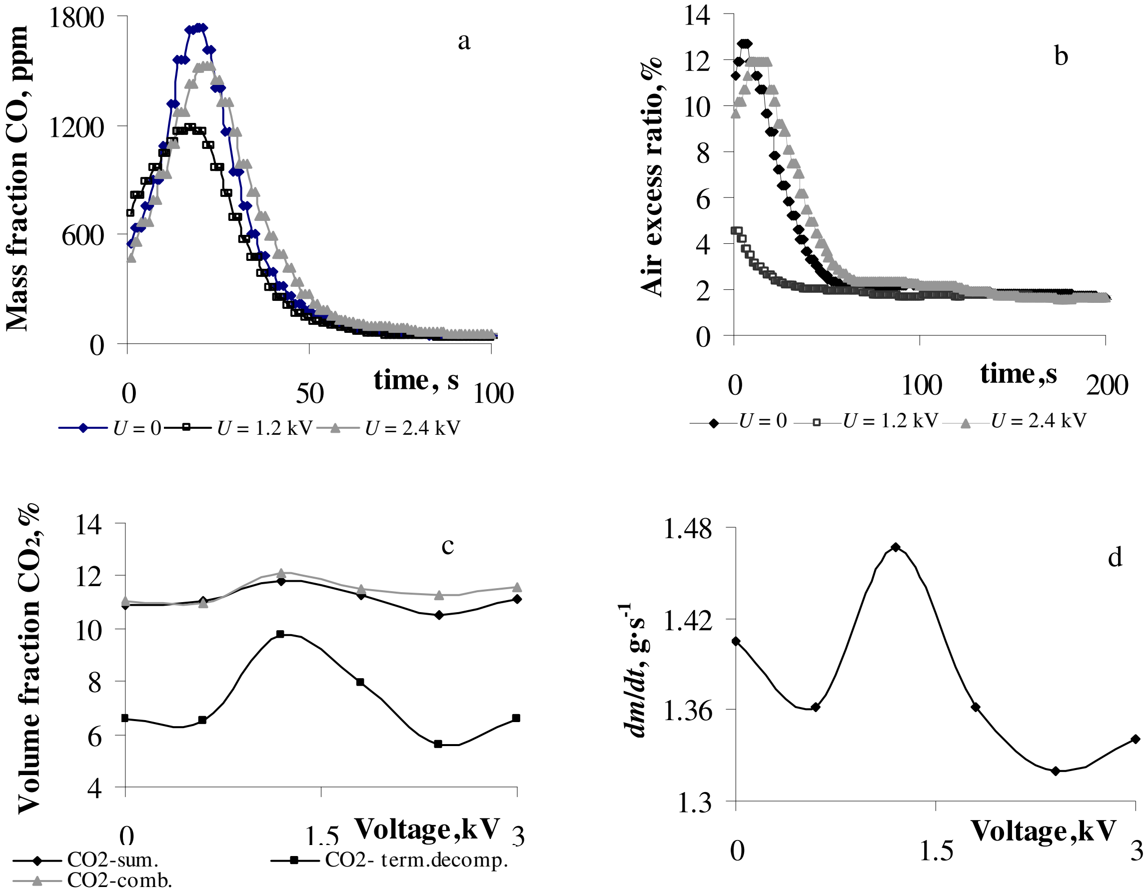

Fig. 2. **DC electric field-induced time-dependent variations of the CO mass fraction (a), air excess ratio (b), the CO_2 volume fraction (c) at different stages of flame formation and the field-enhanced variations of the biomass weight loss rate (d)**

With the constant air supply rate into the combustor, the field-enhanced release of volatiles results in the correlating decrease of the air excess ratio at the bottom of the combustor, thus improving the combustion conditions (Fig. 2-b). This leads to a faster ignition and combustion of volatiles, which are produced at the primary stage of the biomass thermal decomposition with a correlating increase of the

CO_2 volume fraction (Fig. 2-c) and density of the charged flame species at the bottom of the combustor. As a result of the field-enhanced ignition and combustion of volatiles, the electric resistance of the flame reaction zone decreases to 10-100 kΩ with a correlating increase of the ion current in the flame space between the electrodes determining the field-enhanced ion wind formation up to the burner outlet and the formation of the field-enhanced heat and mass transfer to the bottom of the combustor. This, in turn, leads to the enhanced thermal decomposition of biomass pellets, indicating the appearance of a sharp peak of the biomass weight loss rate at the bias voltage of the axially inserted electrode U = 1.2 kV, when the average current in the space between the electrodes increases to $I \approx 2$ mA (Fig. 2-d). At this stage of biomass thermochemical conversion, the field-enhanced increase of the biomass weight loss rate correlates with the linear decrease of the air excess ratio in the flame reaction zone from $\alpha = 2.4$ to $\alpha = 1.7$ and with a correlating increase of the average value of the CO_2 volume fraction in the products by about 10 % (Fig. 2-c).

The field-enhanced thermochemical conversion of biomass pellets results in a correlating field-induced variation of the flame temperature and combustion efficiency. The local measurements of the flame temperature and combustion efficiency have shown that the field-enhanced formation and faster ignition of volatiles at the primary stage of biomass thermal decomposition (t < 100 s) leads to a faster rise of the flame temperature to the peak value (Fig. 3-a) with a pronounced field-enhanced increase of the combustion efficiency at this stage of biomass thermochemical conversion (Fig. 3-b).

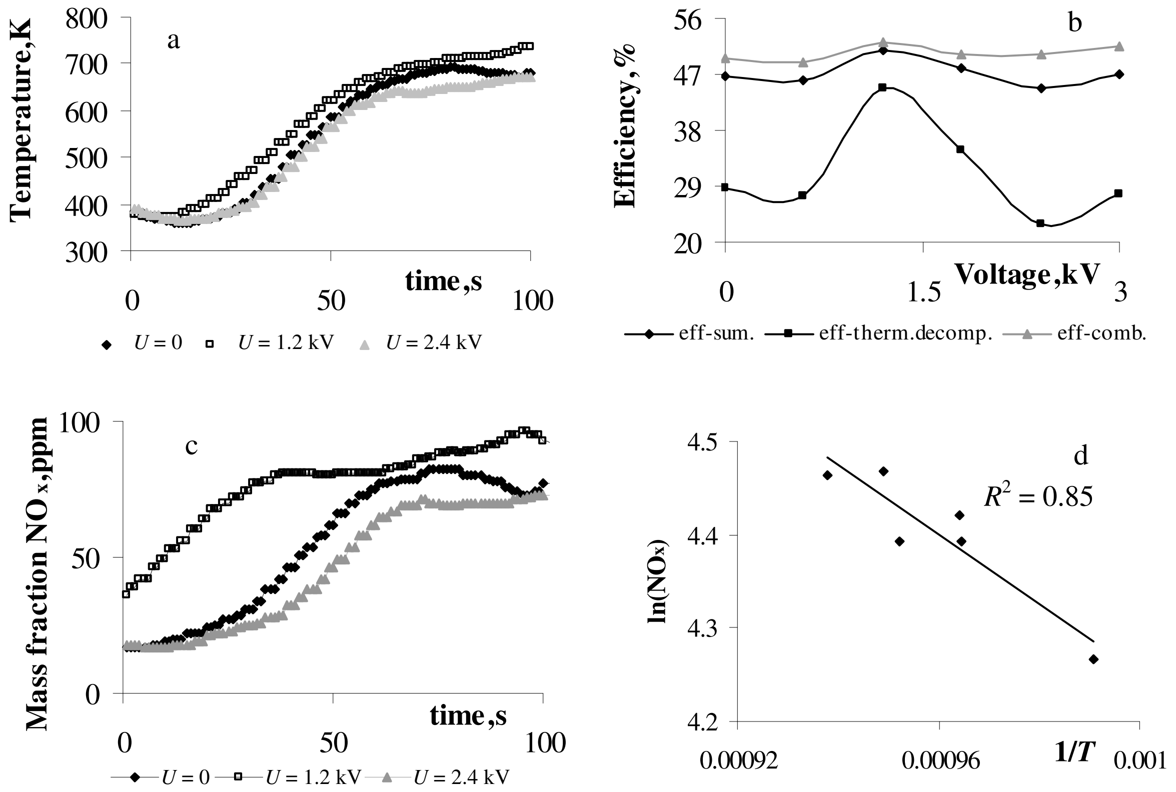

Fig. 3. **DC electric field-induced variations of the flame temperature (a), combustion efficiency (b) and the mass fraction of NO_x in the products (c, d) at different stages of biomass thermal decomposition**.

The field-enhanced temperature increase by about 3-4 % and that of the combustion efficiency by about 4-5 % were observed at the next stage of the volatiles combustion, when the correlating increase of the biomass weight loss by about 4-5 % was observed (Fig. 2-d). This correlation confirms that the field-induced variations of biomass thermal decomposition affect the entire combustion process, including the formation of the temperature-sensitive NO_x emission. A kinetic study of the NO_x emission formation at different stages of biomass thermochemical conversion has shown the dominant field-enhanced formation of NO_x emission just at the primary stage of biomass thermal decomposition

(Fig. 3-c), when the flame temperature is relatively low and does not exceed 800 K (Fig. 3-c). The peak value of NO_x emission at this stage of biomass thermochemical conversion was determined by the peak value of the biomass weight loss and was observed at $U = 1.2$ kV. This correlation between the NO_x formation and the biomass weight loss rate allows suggesting that during the primary stage of biomass thermal decomposition, the NO_x formation can be related to the release and oxidation of fuel-bound nitrogen in woody biomass [18]. A dominant feature of the field-enhanced combustion of volatiles at the next stage of thermochemical conversion of biomass pellets is a correlating field-enhanced increase of the flame temperature and mass fraction of NO_x emission in the products. The peak value of NO_x emission correlates with the peak value of the flame temperature and is observed at $U = 1.2$ kV. The mass fraction of NO_x emission in the products starts to decrease at $U > 1.2$ kV, when the field-induced flame homogenization results in a decrease of the peak and average values of the flame temperature. The field-induced increase of the NO_x mass fraction in the products during the combustion stage of volatiles can be approximately ($R^2 = 0.87$) expressed as a linear dependence of $\ln(NO_x)$ from the flame temperature ($1/T$) (Fig. 3-d), evidencing that the mechanism of NO_x formation during the combustion of volatiles is due to the temperature-sensitive Zeldovich mechanism [18].

Actually, the field-enhanced formation of the temperature-sensitive NO_x emission at field-enhanced thermal decomposition can be classified as a main negative electric field effect on the combustion characteristics, and an optimization of the applied bias voltage and field configuration to provide the homogenization of the flame reaction zone is needed [5] to reduce the peak flame temperature and to limit the formation of NO_x emission.

Conclusions

1. The field-enhanced biomass thermal decomposition, the formation and combustion of volatiles have been investigated experimentally by applying the DC electric field to the flame base.
2. The experimental results lead to the conclusion that the primary electric field effect on the combustion characteristics is a cause of the field-enhanced ion wind motion, determining the field-enhanced heat/mass transfer to biomass pellets, which advances the biomass heating by enhancing the biomass thermal decomposition and the formation of the axial flow of volatiles (CO, H_2).
3. The field-enhanced variation of the biomass weight loss rate with the field-enhanced formation of volatiles at the air excess supply improves the combustion conditions in the flame reaction zone.
4. Improvement of the combustion conditions results in a field-enhanced increase of the volume fraction of CO_2 in the products, combustion efficiency and flame temperature.
5. The field-enhanced increase of the flame temperature leads to a field-enhanced formation of temperature-sensitive NO_x emission at thermochemical conversion of biomass. This is the main negative effect for the given arrangement of the electrodes, and additional measures are required to homogenize the flame reaction zone and to provide the decrease of peak and average values of the flame temperature by limiting the formation of NO_x emission.

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