CHEMICAL ENGINEERING TRANSACTIONS
VOL. 39, 2014
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong

ISBN 978-88-95608-30-3; **ISSN** 2283-9216
DOI: 10.3303/CET1439256

Electric Field-Induced Variations of Combustion Dynamics

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An experimental study of the electric field effect on combustion dynamics at thermo-chemical conversion of biomass pellets was carried out with the aim to determine the DC field effect on the processes of biomass gasification, combustion of volatiles, formation of swirling flame structure, efficiency of heat energy production and composition of polluting emissions. The effect of DC field-enhanced mass transfer of flame species on the formation of swirling flame structure, determining variations of the combustion characteristics, heat energy production and composition of polluting emissions was studied by varying bias voltage and polarity of the axially inserted electrode. The effect of electric field on the flame characteristics has been explained considering the ion wind effects on the interrelated processes of heat/mass transfer determining the formation of the recirculation zone and development of combustion dynamics.

1. Introduction

Previous investigations show (Place and Weinberg, 1965, Lawton and Weinberg., 1969, Jaggers and Von Engel, 1971; Zake et al., 2000; 2005) that application of the DC electric field to the flame results in the formation of electric body force (F) that initiates a field-enhanced drift motion of positively and negatively charged ions ($C_2H_4^+$, $C_3H_3^+$, CHO^+, C_2H^-, O_2^- , etc.) in the field direction. Elastic collisions between the ions and neutral fuel species (CO, H_2, C_xH_y, etc.) result in an effective momentum transfer with field-enhanced variations of the velocity vectors for neutrals producing an interrelated mass flow in the field direction, i.e. the phenomenon named as ionic wind and determining variations of the flame dynamics. The results of experimental study evidence (Zake et al. 2000, 2001) that the DC field-enhanced variations of the flame dynamics promote local variations of the flame composition with direct impact on the flame structure, combustion dynamics, heat energy production and composition of polluting emissions. Moreover, the results of complex experimental study of the electric field effects on flames with the field-enhanced ion drift motion show their potential for the active control of the interrelated processes of flame dynamics, mass transfer, heat transfer and combustion reactions that couple with each other (Cakmakci, 2013; Kim et al, 2010; Berman, 1991) so determining the formation of combustion dynamics. Additionally, a comprehensive research of the field effects on flames for different types of fields (DC, AC and EM) has demonstrated that DC, AC electric and electromagnetic (EM) field effects on flames can include space charge effects at corona discharge and effects of field-enhanced ionization of the flame species that has been an interesting research subject with theoretical importance and practical significance for control of the processes developing at combustion in boilers (Colannino, 2012), in electrostatic air pumps also known as ionic wind pumps (Jewell-Larsen et al, 2004), in internal combustion engines (Bates, 2013), etc. In many combustion devices for enhanced mixing of the flame species and for stabilization of the combustion characteristics, swirling airflows are widely used. The swirl stabilized combustion with high swirl intensity ($S > 0.6$) depends on the formation of a central recirculation zone with swirl-enhanced heat and mass transfer downstream to the bottom of the combustor (Gupta et al, 1984). Such type of flames, with account of the effects of swirl and external forces on the flow dynamics, can be approximately described using a Navier-Stokes system of equations and are reviewed with analysis of the coupling between acoustics, swirling flow dynamics and combustion (Ala Qubbaj, 2005; Syred, 2006).

Please cite this article as: Barmina I., Zake M., Valdmanis R., 2014, Electric field-induced variations of combustion dynamics, Chemical Engineering Transactions, 39, 1531-1536 DOI:10.3303/CET1439256

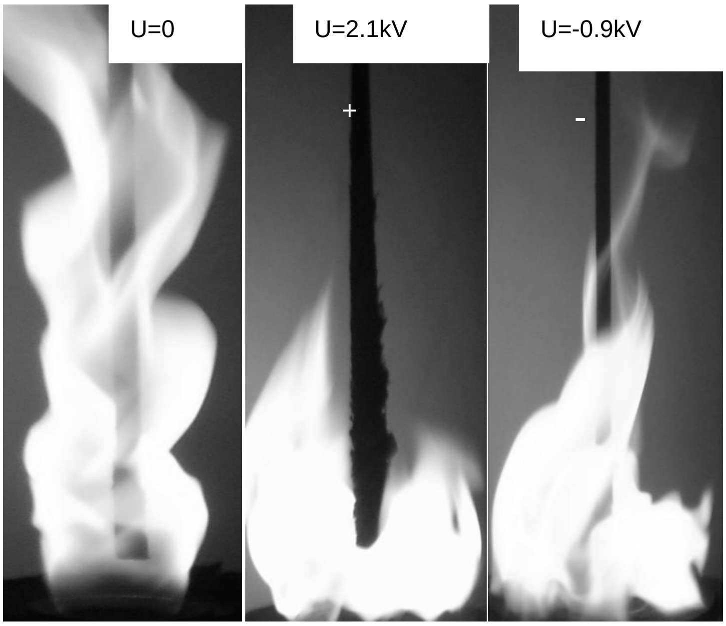

Figure 1: The electric field effect on the swirling flame shape and size.

Previous experimental results on the external electric field effect on the swirling flame formation at high swirl level and combustion of fossil fuel evidence (Zake et al, 2001, 2005) that for such type of flames the field-enhanced mass transfer of gas species in the field direction allows control the swirl-induced recirculation, with direct impact on the flame shape and size (Figure 1), the combustion characteristics, and the formation of greenhouse gas emissions to assure a parametrically optimized swirling combustion. Considering the electric field effects on the swirling flame flow for the combustion of fossil fuel, the recent study aims to provide the active electrical control of the swirling flame flow at gasification and combustion of renewable fuels (biomass pellets) with the electric field-enhanced ionic wind motion confining the flame breakdown and effects which can be related to the field-enhanced excitation and ionization of the flame species. Analysis of the presented results predominately reveals electrodynamic aspects of the interrelated processes of the field-induced variations of the swirling flame dynamics, combustion characteristics and composition of polluting emissions developing at thermo-chemical conversion of biomass pellets.

2. Experimental.

The electric field effect on combustion dynamics is experimentally studied for the thermo-chemical conversion of biomass pellets using a compact pilot device with the inner diameter D = 60 mm, the total length (L) up to 600 mm, and the heat output ranging from 0.5 up to 3.0 kWh. A schematic drawing of the experimental setup is presented in Figure 2. The experimental setup includes a biomass gasifier (1) charged with biomass pellets (500-600 g), a premixed swirling propane/air burner (2) providing additional heat supply into the gasifier, and a sectioned water-cooled combustor (3), downstream of which the dominant burnout of the volatiles is developing. Additional heat energy is supplied by the propane flame flow at the average rate of heat supply 1-1.2 kW injected into the upper part of the layer of biomass pellets to initiate drying, pyrolysis and gasification of the biomass pellets. The primary air is supplied below the layer of the pellets at the air excess ratio $\alpha \approx 0.4$-0.6 to support the process of biomass gasification and initiate the formation of the axial flow of the volatile compounds (CO, H_2 and different fragments of hydrocarbons C_xH_y). The volatiles' combustion process is strengthened by the secondary swirling air supply at the bottom of the combustor through the tangential inlets. The air excess ratio in the flame reaction zone can be varied from $\alpha \approx 1$ to $\alpha \approx 2.5$. The secondary swirling air in the combustor is supplied at a high swirl level ($S \approx 0.6$-1) determining the formation of the recirculation zone at the bottom of the combustor with the swirl-enhanced mixing of the flame compounds.

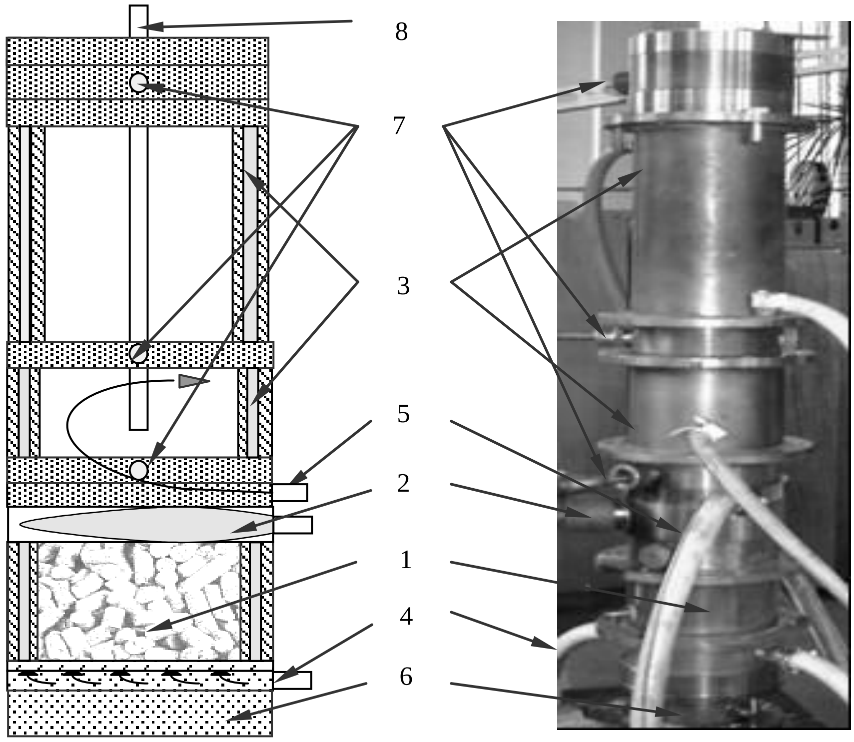

Figure 2: Schematic drawing and digital image of the experimental device for gasification and combustion of biomass pellets: 1 – gasifier of biomass pellets; 2 - inlet of propane flame flow; 3 – combustor water-cooled sections; 4 - primary air supply nozzle; 5 – secondary air supply nozzle; 6 - ash vessel; 7 - orifices for diagnostic tools; 8 - central electrode

The electric field effect on the combustion dynamics was studied using an axially inserted electrode. The bias voltage and polarity of the electrode relative to the water-cooled walls of the combustor can be varied in the -3 - +3 kV range, while the ion current in this study is limited to 0.3 mA to minimize the field-induced Joule dissipation and restrict the gas discharge formation.

The experimental study of the electric field effect on the swirling flame flow is combined with research of the field-induced variations of the interrelated processes of flame dynamics, combustion of volatiles, heat energy production and composition of polluting emissions. The electric field effects on these processes are estimated from the joint measurements of the flame velocity, temperature and composition profiles by varying the polarity and bias voltage of the axially inserted electrode. The field effect on the produced heat energy is estimated from the calorimetric measurements of the cooling water flow at different stages of the swirling flame formation and thermo-chemical conversion of biomass pellets. The diagnostic tools used in this study are Pt/Pt-Rh thermocouples for local time-dependent measurements of the flame temperature, a portable gas analyzer Testo 350XL with a Pitot tube for measuring the formation of the flame velocity profiles, combustion efficiency, flame temperature and composition of emissions (v, T, CO, CO_2, NO, NO_x, O_2). The time-dependent variations of the flame temperature and cooling water flow temperature are recorded using a computer data acquisition system PC-20TR. The online measurements of the main parameters were carried out with average accuracy up to ±5% and R squared value R^2≈0.95-0.99.

3. Results and discussion.

If the electric body force (F) is applied to the swirling flame of the volatiles produced at thermo-chemical conversion of biomass pellets, the primary field effect on the combustion dynamics can be related to the variation of the flow conditions and flame dynamics. By analogy with the field effect on the swirling propane flame flow, at the high swirl level of the flame of volatiles (S > 0.6), the electric body force acts on the flame recirculation zone determining variations of the flame shape and length, as well as the formation of the flame velocity profiles.

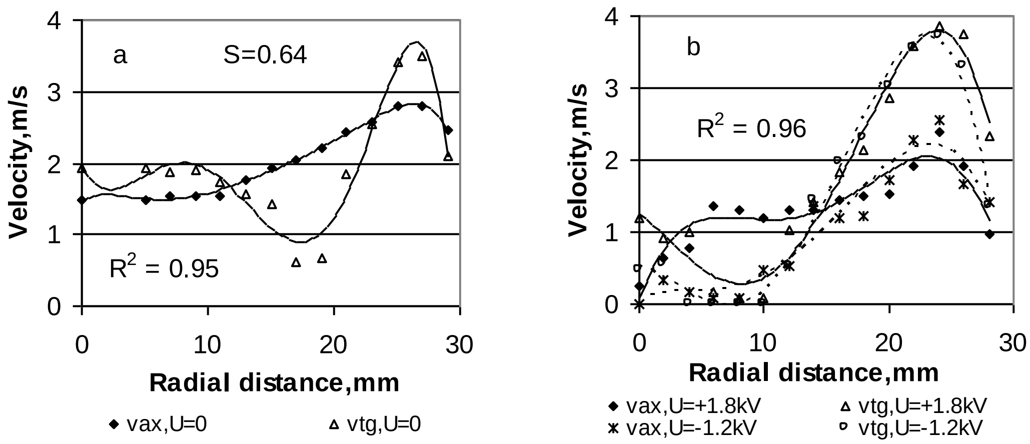

Figure 3: The electric field-induced variations of the swirling flame velocity profiles at the primary stage of swirling flame formation (L/D ≈ 0.6).

As follows from Figure 3-a, both the axial and the tangential flame velocity close to the bottom of the combustor (L/D ≈ 0.6) show the occurrence of peak values at the outer shear layer with a decrease towards the water-cooled channel walls of the combustor. Moreover, an increase of the tangential velocity is observed close to the flame axis that can be related to the swirl flow reversing from the layer of the biomass pellets (Zake, 2009). If the electric field was applied to the swirling flame flow, the field-enhanced decrease of the axial and tangential flame velocity close to the flame axis R < 10 mm with radial expansion of the air swirl motion towards the flame axis was observed (Figure 3-b). The most pronounced decrease of the axial flame velocity close to the flame axis was observed with the positive bias voltage of the central electrode, indicating that the electric body force promotes the field-enhanced reverse axial motion of the flame species (positive ions and neutrals) to the layer of biomass pellets by counter-balancing the axial flow of the volatiles produced at the thermo-chemical conversion of biomass and field-enhancing mixing of the flame compounds (Figure 3-a, b). There is a clear evidence of the interrelated field-enhanced processes of heat/mass transfer resulting in the increase of the flame temperature at the bottom part of the swirling flame flow (L/D = 0.25). The averaged values of the flame temperature close to the biomass layer increased from T = 1300 K at U = 0 to T = 1400 K at U = +0.6 kV. A less pronounced increase of the averaged values of the flame temperature up to T = 1315 K was observed with the positive bias voltage of the central electrode and field-enhanced drift motion of negative ions.

The field-induced interrelated processes of heat and mass transfer up to the biomass surface with a correlating increase of the flame temperature at the combustor bottom with the biomass layer advanced the field-enhanced thermal decomposition of the main components (hemicellulose, cellulose) of lignocellulosic biomass increasing the average rate of the biomass weight loss from 0.18 g/s to 0.19 g/s and providing a more intensive release of the volatiles (H_2, CO) (Figure 4-a). Similar results were achieved at the thermo-chemical conversion of pelletized agricultural residues and herbaceous biomass. Under the conditions of field-enhanced thermal decomposition of biomass pellets with the enhanced mixing of the flame components at the combustor bottom, the field-enhanced ignition and combustion of the volatiles were observed, which increased the average value of the CO_2 volume fraction in the products (Figure 4-b). With the positive bias voltage of the axially inserted electrode, the average CO_2 volume fraction in the products increased from 10.4 % at U = 0, approached the peak value 12.04 % at U = 1.2-1.8 kV and started to decrease at a higher bias voltage of the axially inserted electrode. The decrease of the CO_2 volume fraction in the products correlates with the increase of the air excess in the flame reaction zone (up to 120%), whereas the temperature of the flame reaction zone and the temperature of the products (Figure 4-b,c) both decrease. The average value of the combustion efficiency with field-enhanced mixing of the flame compounds and combustion of the volatiles increased from 79.5 % at U = 0 to the peak value 81.2 % at U = +0.9 kV. The field-enhanced thermo-chemical conversion of biomass pellets and the combustion of volatiles resulted in a correlating increase of the produced heat power from the average value 1.6 kJ/s at U = 0 up to 1.7 kJ/s at U = +1.8 kV.

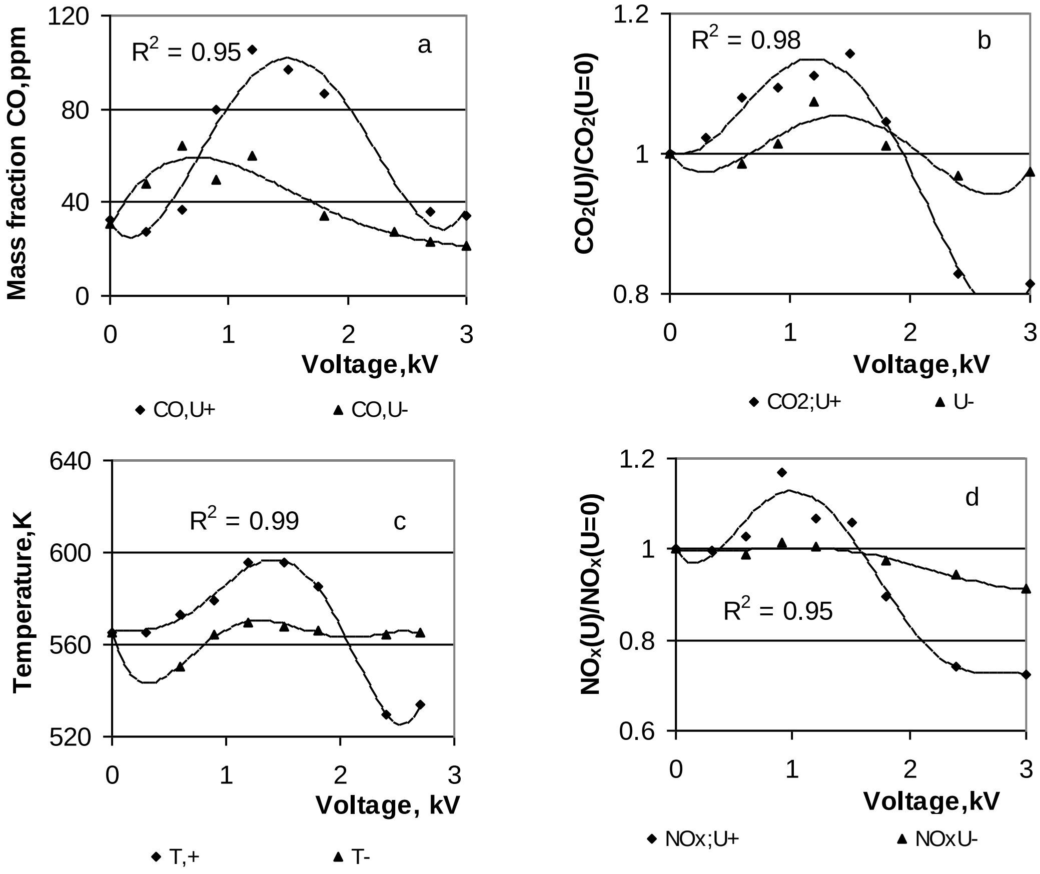

Figure 4: Field-enhanced variations of the formation (a) and combustion (b) of volatiles at thermo-chemical conversion of biomass (softwood) pellets by varying the polarity of the axially inserted electrode; (c, d) the electric field effect on the temperature close to the biomass layer and NO_x formation.

It should be noted that a more effective increase of the heat power at the thermo-chemical conversion of biomass pellets was observed at the end stage of char conversion of the biomass pellets. In all cases, the field-enhanced combustion of the flame components has verified its influence on the temperature-sensitive reactions of nitrogen oxides formation (Zake, 2009), promoting the field-enhanced increase of the mass fraction of NO_x emissions, that approached the peak value (84 ppm) at U = +0.9 kV and began to decrease at U > +0.9 kV (Figure 4-c).

4. Conclusion

The experimental study of the field-enhanced variations of the combustion dynamics at thermo-chemical conversion of biomass pellets was carried out to ascertain the field effect on the flame dynamics, formation and combustion of the volatiles, and on the heat energy production.

Measurements of the flow patterns demonstrate the field-enhanced decrease of the axial and tangential velocity components close to the flame axis indicating the formation of field-enhanced reverse interrelated heat/mass transfer of the flame species promoting the variations of the flame temperature in the vicinity of the biomass layer with direct impact on the thermal decomposition of biomass pellets and on the combustion of the volatiles.

A more pronounced field-enhanced thermal decomposition of biomass is observed with positive bias voltage of the central electrode, testifying the formation of the temperature peak value with the enhanced release and combustion of the volatiles at U = 0.9-1.8 kV. The field effect on the thermo-chemical conversion of biomass starts to decrease at higher bias voltage when the field-enhanced swirl flow reversing enhances the air excess at the bottom of the combustor with flame cooling that restricts the thermo-chemical conversion of biomass pellets.

Acknowledgements

The authors would like to express their gratitude for the financial support from the Latvian Research Cooperation Project of Latvian Council of Science Nr 623/2014.

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