THE ELECTRIC FIELD EFFECT ON COMBUSTION DYNAMICS

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Abstract: The DC electric field effect on the development of combustion dynamics downstream the swirling flame flow is studied experimentally with the aim to provide the complex electric field control of the swirling flame dynamics, flame structure, temperature, composition, processes of heat/mass transfer and heat energy production at thermo-chemical conversion of biomass pellets. The mechanism of field effect on the combustion characteristics is discussed with account of field-induced ion drift motion in the field direction providing electric control of the flame structure, composition and main combustion characteristics at thermo-chemical conversion of biomass pellets.

1. Introduction

The DC and AC electric field effects on different types of fuel combustion in the engines, turbines, boilers and furnaces have been investigated to provide combustion control to improve combustion conditions and flame stability [1-9]. Various experimental and numerical studies confirm that the electric field-induced "ionic wind" phenomenon [1, 6, 8] strongly affects the flame shape, dynamics, the formation of polluting NO_x emission, soot formation and processes of interrelated heat/mass transfer. In typical furnaces and boilers, this means electrodynamic control of heat/mass transfer at a relatively low applied power that is less than 0.1% of the thermal power produced by fuel combustion [7]. Since the electric field provides the enhanced heat/mass transfer in the field direction, one may use electric field control technology to enhance the heat transfer to the boiler tubes or protect the critical engine parts from heat fluxes. In addition to field-enhanced control of the processes of heat/mass transfer, the field-enhanced variation of flow dynamics allows to control the residence time of reactions by promoting or by limiting the reactions that lead to the NO_x and CO formation. Motivated by the field-induced variations of flame dynamics and processes of heat/mass transfer, the main objective of the present work is to provide a complex experimental study of the field-induced processes of the thermal decomposition of biomass pellets and thermo-chemical conversion of produced volatiles (CO, H_2). The previous study of the electric field effect on the combustion of volatiles has been carried out with high swirl intensity ($S > 0.6$) determining the formation of a toroidal recirculation zone close to the flame base [4, 5], with field-induced variations of heat/mass transfer and flame structure. The present study is focused on the electric control of the formation of lean partially premixed swirling flame of the volatiles at low swirl intensity ($S < 0.6$) by operating below the vortex breakdown threshold [10]. The DC electric field effect on the thermal decomposition of biomass and formation of main combustion characteristics is analyzed by varying the applied voltage and polarity of the axially inserted electrode.

2. Experimental

The electric field effect on the combustion dynamics at thermo-chemical conversion of biomass pellets was studied experimentally using a compact pilot setup that includes a biomass gasifier charged with biomass pellets and a sectioned water-cooled combustor, downstream of which the dominant burnout of the volatiles develops [11, 12]. The propane flame is used as an external heat energy source for additional heat energy supply (1.2 kJ/s) into the upper part of biomass with the aim to initiate thermal decomposition of pelletized biomass. To provide the air excess ratio $\alpha \approx 0.4$-0.6, the primary air is supplied at an average rate of 28-30 l/min under the biomass layer to support the process of biomass gasification and initiate the formation of axial flow of the volatile compounds (CO, H_2). The volatiles' combustion is supported by the secondary swirling air supply at an average rate of 34-35 l/min through the tangential inlets at the combustor bottom. The secondary air supply provides the lean combustion conditions in the flame reaction zone, with the air excess ratio $\alpha \approx 1.5$-1.8. The electric field effect on the combustion dynamics was studied using an electrode of 150 mm total length axially arranged through the biomass layer, with the electrode top close to the flame base promoting complex field-enhanced variations of the biomass thermal decomposition, flame dynamics and swirl flow structure. The bias voltage and polarity of the electrode relative to the grounded water-cooled walls of the device can be varied in the -2.7 - +2.7 kV range, while the ion current in this study is limited to 1-1.5 mA to minimize the effects of Joule dissipation and corona discharge on the processes of biomass thermo-chemical conversion.

The diagnostic tools used in this study are Pt/Pt-Rh thermocouples for local time-dependent measurements of the flame temperature, a portable air flowmeter Testo 453 with a Pitot tube for measuring the formation of flame velocity profiles, Testo 350-XL for local measurements of the combustion efficiency, flame temperature (T) and flame composition, i.e. mass fraction of the main volatiles CO, H_2, NO_x, fragments of unburned hydrocarbons and volume fraction of the main product CO_2. To estimate the total amount of heat energy produced at thermo-chemical conversion of biomass pellets, calorimetric measurements of the cooling water flow were made providing measurements of time-dependent variations of the flame temperature and of the cooling water flow temperature that were recorded using a computer data acquisition system PC-20TR. All measurements of the DC electric field effects on the gasification and combustion characteristics were made at constant average axial and tangential airflow rates, determining the swirl number of the undisturbed inlet flow $S < 0.6$.

3. Results and discussion

With the given field configuration, the primary DC field effect on thermo-chemical conversion of biomass pellets can be related to the field-enhanced thermal decomposition of biomass pellets. The DC field-enhanced thermal decomposition results in an increase of the biomass mass loss rate (dm/dt), which can be approximated by a linear dependence on the applied bias voltage at high R-squared values ($R^2 \approx 0.96$). By increasing the bias voltage up to ±2.7 kV, the average mass loss rate of biomass pellets can be increased by 12-16% determining the field-enhanced formation of axial flow of the volatiles injected into the combustor at the average axial flow rate 1.2 m/s close to the flame base, with the low swirl number ($S \approx 0.3$). For the fuel-lean conditions with the high level of air excess (150-170%) in the undisturbed flame reaction zone (U = 0), the field-enhanced formation of the volatiles resulted in a decrease of the air excess by ~25%, improving the volatiles' combustion conditions. As a consequence of the field-enhanced thermal decomposition of biomass, a faster ignition of the volatiles with a faster rise of the flame temperature, volume fraction of CO_2 and produced heat power up to their peak values was observed (fig.1). Moreover, the measurements of the total amount of the produced heat energy revealed a linear correlation between the field-enhanced variations of the biomass weight loss and the produced heat energy at thermo-chemical conversion of the volatiles.

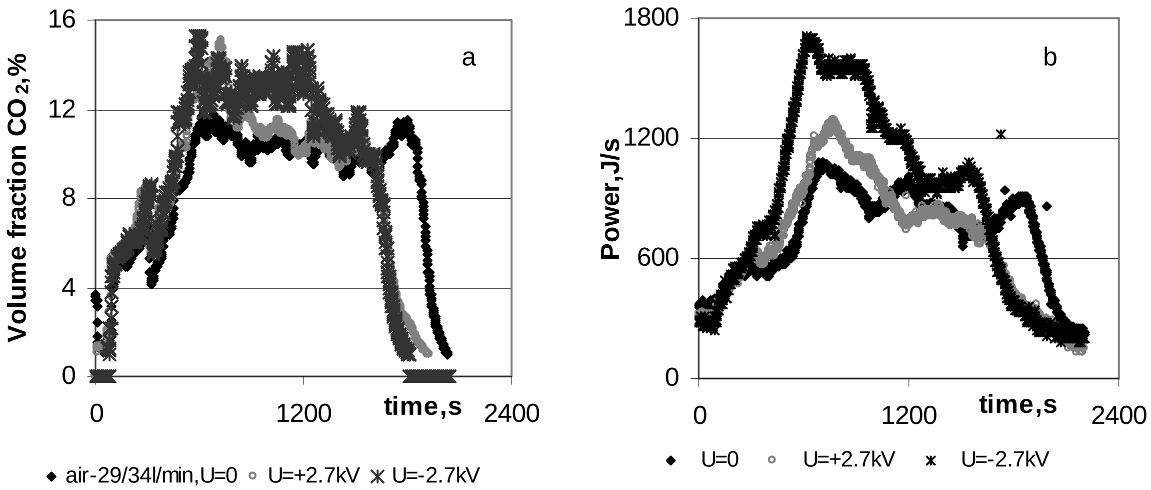

Figure 1: DC electric field effect on the kinetics of CO_2 formation (a) and heat power production (b) at thermo-chemical conversion of biomass pellets.

In addition to the DC field-enhanced thermal decomposition of biomass pellets, the field-enhanced variations of the flame structure were observed. Increasing the negative bias voltage of the axially inserted electrode promoted the radial expansion of the flame reaction zone with the correlating increase of the axial flow velocity average values (u) from 0.7 m/s to 0.84 m/s, while the tangential flow velocity average values (w) decreased from 0.62 to 0.35 m/s, so decreasing the swirl intensity. The field-enhanced radial expansion of the flame reaction zone resulted in the correlating increase of the flame temperature and volume fraction of CO_2 along the outside part of the flame reaction zone at $r/R > 0.5$ (fig. 2a, c, e). The field-enhanced radial expansion of the flame reaction zone towards the positively biased channel walls allows to suggest that the field-enhanced thermal decomposition of biomass pellets would promote the formation of negatively charged fragments of unburned hydrocarbons (CHO_2^-, CHO_3^-) as well as of negative ions of O_2^-, OH^-, and O^-), with the field-enhanced heat/mass transfer (ionic wind) towards the channel walls. The reverse DC field effect on the heat/mass transfer and flow dynamics was observed for positive bias voltage of the axially inserted electrode. In this case, the dominant feature of the field effect on the flame formation was a field-enhanced decrease of the axial flow velocity average value from 0.96 m/s to 0.81 m/s, with the correlating increase of the tangential flow velocity average value from 0.3 m/s to 0.43 m/s, so enhancing the swirl intensity and field-enhanced mixing of the flame compounds. With the low swirl number, the field-enhanced mixing of the flame compounds predominately occurred along the outside part of the flame reaction zone (at $r/R \approx 0.6$) and supported the enhanced thermo-chemical conversion of the volatiles, determining local decrease of free oxygen below 6%, increase of the flame temperature, the volume fraction of CO_2 up to their peak values and the field-enhanced formation of the annular reaction zone at $r/R \approx 0.4$-0.7 (fig. 2b, d, f). In fact, the field-enhanced temperature local increase correlates with the local increase of the rate of temperature-sensitive NO_x formation, so increasing the average mass fraction of NO_x emission in the products by ~7-8%.

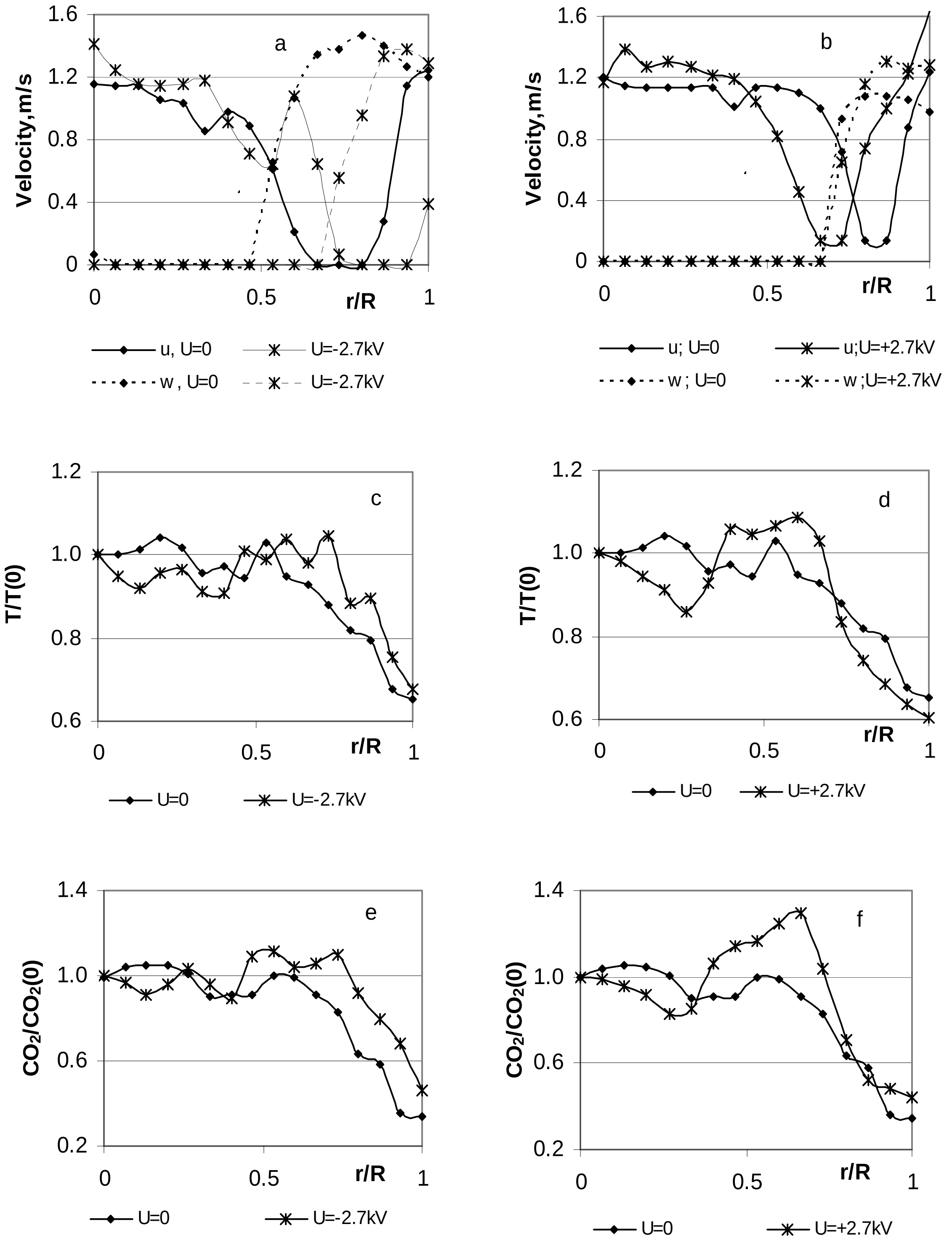

Figure 2: DC electric field effect on the formation of flame velocity (a, b), temperature (c, d) and composition (e, f) profiles at constant bias voltage (U = ±2.7 kV) and variations of DC field polarity.

Conclusion

Based on the results obtained, the following conclusions on the DC electric field effect on the thermo-chemical conversion of biomass pellets at the low swirl number of the swirling flame flow (S < 0.6) can be drawn.

The DC field effect on the thermo-chemical conversion of biomass pellets develops as a multistage process, determining the primary effect of biomass field-enhanced thermal decomposition with field-enhanced formation and thermo-chemical conversion of volatiles, promoting a faster ignition with a more complete combustion of the volatiles and a higher amount of the produced heat energy in the flame reaction zone.

The process of thermo-chemical conversion of the volatiles is influenced by the field-induced variations of the flame dynamics, with field-enhanced variations of the processes of heat heat/mass transfer determining the formation of flame velocity and composition profiles, flame shape and structure. The field-enhanced radial mass transfer to the channel walls, with radial expansion of the flame reaction zone and homogenization of the flow structure, dominates at negative bias voltage of the axially inserted electrode, whereas positive bias voltage with field-enhanced mass transfer of the flame species towards the flame axis reduces the width of the reaction zone the field-enhanced mixing of the flame compounds and local variations of the flame composition along the outside part of the reaction zone with field-enhanced formation of the annular reaction zone.

Acknowledgments. The authors would like to acknowledge the financial support from Latvian research grant N623/1.

4. References

[1] Lawton, J.; Weinber, F.J.: Electric Aspects of Combustion. Clarendon Oress, Oxford, 1969.

[2] Place, E.R.; Weinberg, F.J.: Electrical control of flame carbon, Proc. Royal Society, vol. 289A (1965), pp. 192-205.

[3] Won, S.H.; Cha, M.S.; Park, C.S.; Chung, S.H.: Effect of electric fields on reattachment and propagation speed of tribrachial flames in laminar coflow jets, Proc. the Combustion Institute, vol. 31 (2007), 963-970.

[4] Zake, M.; Barmina, I.; Turlajs, D.: The electric field control of the polluting emissions from the flame, Global Nest, 2001, vol.3, N2, pp.95-108.

[5] Zake, M.; Barmina, I.; Turlajs, D.; Lubane, M.; Krumina, A.: Swirling flame: Part 2. Electric field effect on the soot formation and greenhouse emission, Magnetohydrodynamics, vol.40 (2004), 182-2002.

[6] Zhang,Y; Wu, Y.; Yang, H.; Zhang, H.; Zhu, M.: Effect of high-frequency alternating electric fields on the behavior and nitric oxide emission of laminar non-premixed flames, Fuel, vol.109 (1013), 350-355.

[7] Colannino J., 2012. Electrodynamics Combustion Control TM Technology, In: A Clear Sign White Paper, 1-8.

[8] Vatazhin, A.B.; Likhter, V.A.; Sepp, V.A.; Shulgin, V.I. Effect of an electric field on the nitrogen oxide emission and structure of a laminar propane diffusion flame, Fluid Dynamics, vol. 30 (1995), 166-174.

[9] Bates S.C., 1993, Energy Fields Effects in Internal Combustion Engines, Final Report of Consulting Research for ORNL, Subcontract 80X-SN737V, 1-13. In: http://www.tvu.com/PEFinEng.html

[10] Cheng, R. K., Yegian , D. T., Miyasato , M. M., Samuelsen , G. S., Pellizzari , R., Loftus, P. and Benson, C. (2000).Scaling and Development of Low-Swirl Burners for Low-Emission Furnaces and Boilers. Proc. Comb. Inst. 28: 1305 -1313.

[11] Barmina, I., Lickrastina, A., Purmalis, M., Zake, M., Valdmanis, R., Valdmanis, J., Arshanitsa, A., Solodovnik, V., & Telysheva, G. (2012). Effect of biomass high-frequency pre-treatment on combustion characteristics. Chemical Engineering Transactions, 26, 895-900.

[12]] Barmina, I., Lickrastina, A., Zake, M., Arshanitsa, A., Solodovnik, V., & Telysheva, G. (2013) Experimental study of the thermal decomposition and combustion of lignocellulosic biomass pellets, Latvian Journal of Physics and Technical Sciences, vol. 50, no. 3, pp.35-49.