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ELECTRIC FIELD EFFECTS ON THE SWIRLING COMBUSTION DYNAMICS

LIESMAS VIRPUĻPLŪSMAS DEGŠANAS PROCESA DINAMIKA ELEKTRISKĀ LAUKĀ

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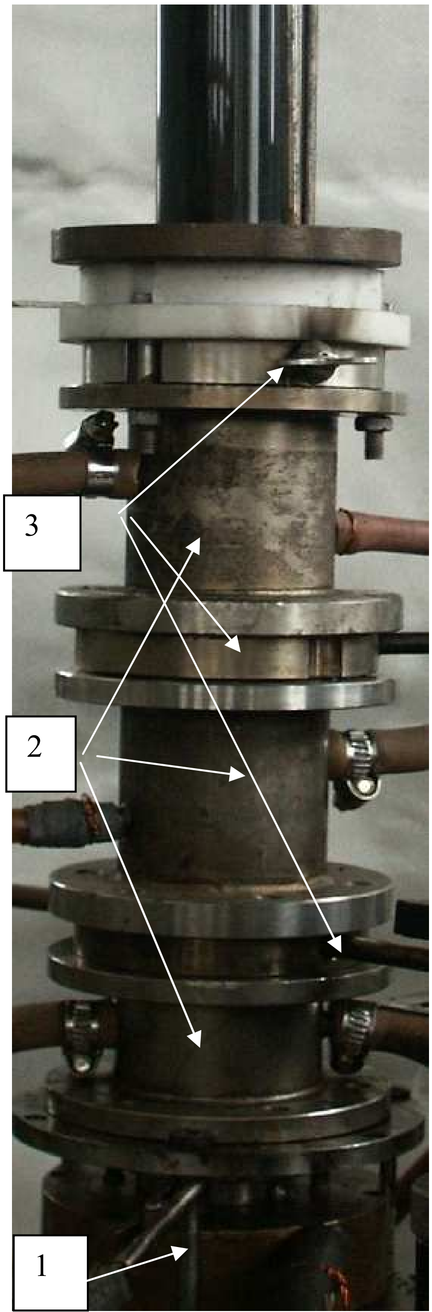
Introduction

The application of swirl combustion with high swirl intensity and toroidal recirculation zone has been extensively used for efficient and stable combustion in industrial furnaces, utility boilers and heat exchangers. The numerical simulation of the premixed, non-premixed and partially premixed swirling flame flows are carried out and analyzed [1-3] in order to determine the role of swirl on the swirling flow field formation and its influence on combustion processes and composition of the polluting emissions. The results of CFD have shown that the degree of premixing controls the thermal field uniformity, flame stability limits and corresponding emission levels.

Moreover, global flame features and combustion emission levels are highly affected by burner geometry and operational parameters determining the swirl intensity and the flow field that exhibits a very complex structure with high swirl intensity near the walls and reverse axial flow formation. The previous research effort refers to the experimental study of the non-premixed swirling flame formation by varying operational parameters of the swirl burner – by varying the rates of fuel and air supply and mixing rate of the flame compounds. An enhanced fuel flow and air swirl mixing had been achieved by increasing the swirling air supply at a constant rate of the axial fuel supply into the burner, thus enhancing the reverse axial flow formation, completing the fuel combustion and by limiting the rate of soot formation downstream the fuel-rich flame core [4]. The additional control of the flame formation had been obtained by using the electric field effects on the formation of the swirling flame flow field with direct influence on the recirculation of the hot products, mixing rate of the flame compounds and combustion dynamics [5].

Actually, the experimental study of the electric field effects on the non-premixed swirling flame formation have shown that the swirl-enhanced variations of the recirculation can be used as a tool to provide control of the mixing rate of flame compounds and residence time of reactions by enhancing or limiting the fuel burnout.

Recent experimental study is aimed at understanding of the electric field effects on the formation of the partially premixed swirling flame velocity, temperature and composition fields and basic mechanisms that control the interrelated processes of the swirling flow dynamics, fuel combustion and processes of heat/mass transfer, depending on the bias voltage and polarity of the axially inserted electrode.



Experimental device

The electric field effect on the combustion dynamics is experimentally studied using an experimental device that is composed of the swirl burner and water-cooled sections of total length up to 350 mm (Fig.1). Between the water-cooled sections are inserted sections with orifices that allow injection of different diagnostic tools (thermocouples, Pitot tubes, electric probes, gas analyzer probes) into the swirling flame flow and provide the local measurements of the flame velocity, temperature and composition fields. The six orifices of 1mm in diameter inside the burner nozzle are used to provide the radial fuel supply into the burner that rapidly mixes with the swirling airflow, injected into the bottom part of the burner nozzle through the eight tangential inlets of 3mm in diameter. Because of relatively high swirl intensity of the flame flow at the burner outlet ($S \approx 1$), the formation of a toroidal recirculation zone close to the burner outlet (L=5-10 mm) is observed.

The swirling flame flow from the burner outlet issues into the channel section (Fig.1), downstream of which is axially inserted a steel electrode. The bias voltage and polarity of the axially inserted electrode in this study can be varied in a range from –3 kV up to +3 kV, while the ion current is limited to 0,2 mA. The investigations of the electric field effect on the flame dynamics and fuel combustion involve an experimental study of the field effects on the formation of the flame velocity, temperature and composition fields, using a Pitot tube for local measurements of the flame velocity, Pt-Pt/Rh (10%) thermocouples for local measurements of the flame temperature and a gas analyzer Testo-350-XL for local measurements of the composition of polluting emissions and efficiency of the fuel burnout. The electric field effects on the heat transfer are estimated from calorimetric measurements of the cooling water flow. All experimental data are recorded using the data recording system PC-20TR. A high voltage DC source provides the requested voltages and polarity of the electrodes.

Figure 1. The digital image of the experimental device: 1- swirl burner; 2-water-cooled channel sections; 3- diagnostic sections with orifices for diagnostic tools.

Experimental results and discussion

A series of experiments were carried out in order to examine the basic mechanisms, which control the combustion dynamics and the formation of polluting emissions, when the DC electric field is applied to the swirl stabilized near-premixed propane/air flame flow by enhancing or confining the axial and radial drift motion of the positively and negatively charged flame species, such as $C_3H_3^+$, $C_2H_4^+$, $C_2H_2^+$, CHO^+, H_3O^+, O_2^-, etc. with mean density of charged flame species in a flame reaction zone up to $n_{e,i} \approx 10^{18}$-10^{19} m^{-3}. The elastic collisions between the field-enhanced the flame ions and neutral compounds result in momentum exchange by enhancing or confining the interrelated processes of heat/mass transfer in a field direction with direct influence on the flame shape and size (Fig.2) and so on the flame velocity, temperature and composition profiles, local rates of reactions and processes of heat/mass transfer.

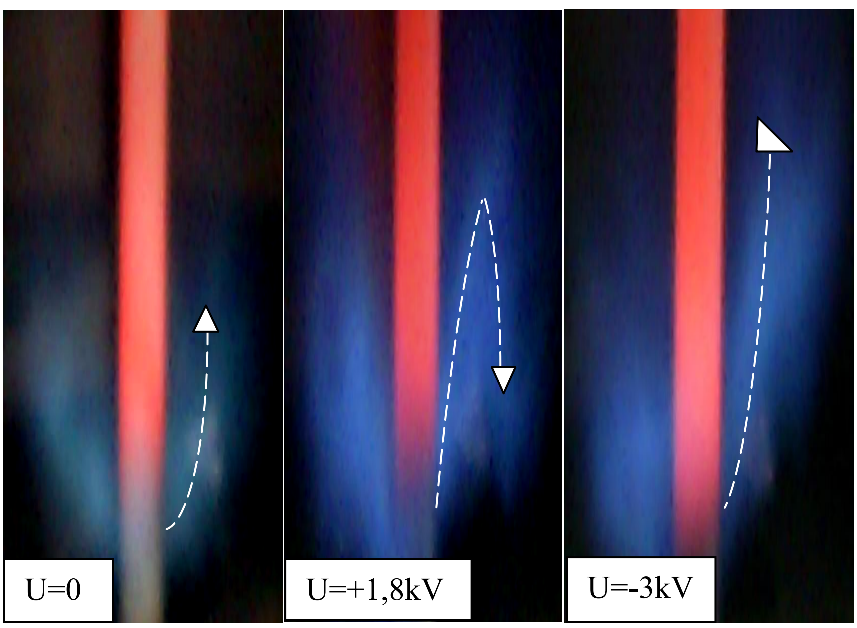


Figure 2. The digital image of the electric field effect on the shape and size of the free premixed flame.

The digital image of the near-premixed free swirling flame flow close to the burner outlet (up to L/D=2) shows the formation of a tulip-shaped pyrolysis zone with an intensive blue radiation of C_2 (λ=516 nm) and CH^* radicals (λ=431.2nm) and the formation of the central reaction zone, where dominates the infrared band radiation of the main products (CO_2, CO, H_2O) (Fig.2.). With the electric field applied to the free swirling flame flow are detected the variations of the flame shape, length and radiation intensity (Fig.2.). Moreover, for the positive bias voltage of the axially inserted electrode the electric field enhances the reverse axial flow formation along the outside part of the flame towards the negatively biased surface of a burner. The less pronounced variations of the flame shape are detected for the negatively biased central electrode (Fig.2.).

The experimental study of the dynamics of the undisturbed swirling flame channel flow indicates the high swirl intensity of the burner outlet flow ($S \approx 2/3\ v_{tg}/v_{ax} \approx 1$) up to L/D=1,5, determining the reverse axial flow formation close to the flame centerline with an intensive tangential flow formation close to the channel walls. Typical shape of the velocity profiles close to the burner outlet (L/D=0,5) is illustrated in Figure.3. As one can see from Figure 3, the typical feature of the partially premixed propane/air flame dynamics is the formation of the outer shear layer of the burner outlet flow (R>5mm) with pronounced gradients of the flame velocity compounds, determining intensive turbulent mixing of the flame compounds and combustion dynamics.

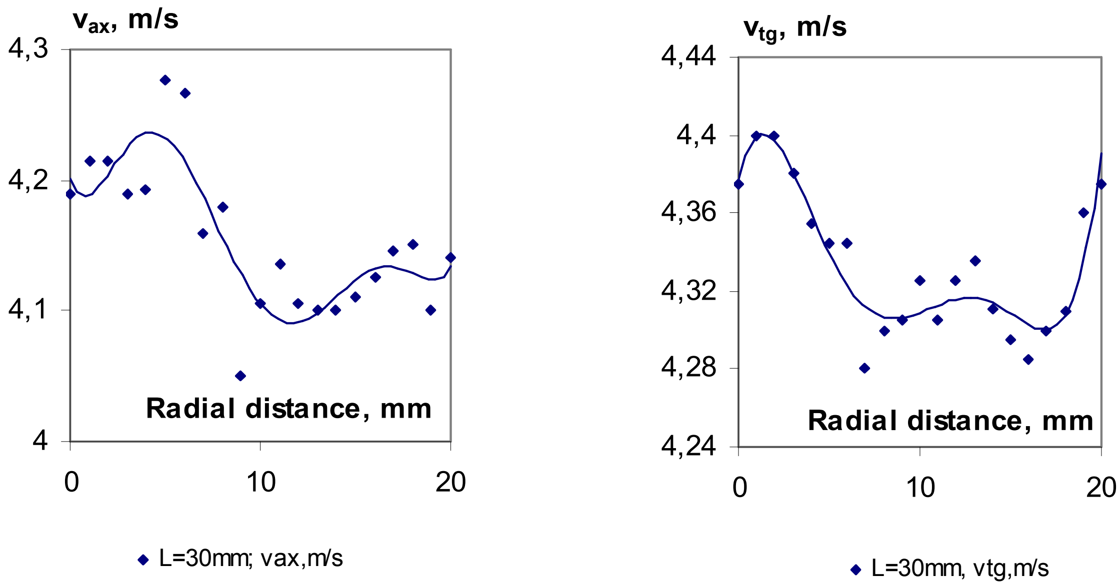


Figure 3. Typical shape of the swirling flame velocity profiles close to the burner outlet (L/D=1,5).

At the initial stage of the swirling flame flow formation- up to L/D=2 the most intensive heat release with the peak flame temperature (T=1550-1600K) and peak combustion efficiency is fixed close to the flame axis (R<10 mm) with correlating increase up to peak value the mass fraction of the main products (CO_2, NO_x) (Fig.4.).

Further downstream is observed the radial flame flow expansion by increasing combustion efficiency and mass fraction of the main products along the outside part of the swirling flame flow (R>10 mm) Fig.4.).

The dominant feature of the electric field effect on the formation of the premixed swirling flame dynamics is the enhanced formation of the reverse axial flow, promoting a gradual decrease of the axial flame velocity for the positive bias voltage of the axially inserted electrode (Fig.5.) and the radial flame expansion with enhanced radial mass transfer of the flame species. The reverse field effect on the flame axial velocity is detected for the negative bias voltage of the axially inserted electrode, when the electric field enhances the mass transfer of the flame species downstream the flame axis, while slightly decreases the flame length, as it is observed for the conditions of the free swirling flame flow (Fig.2.).

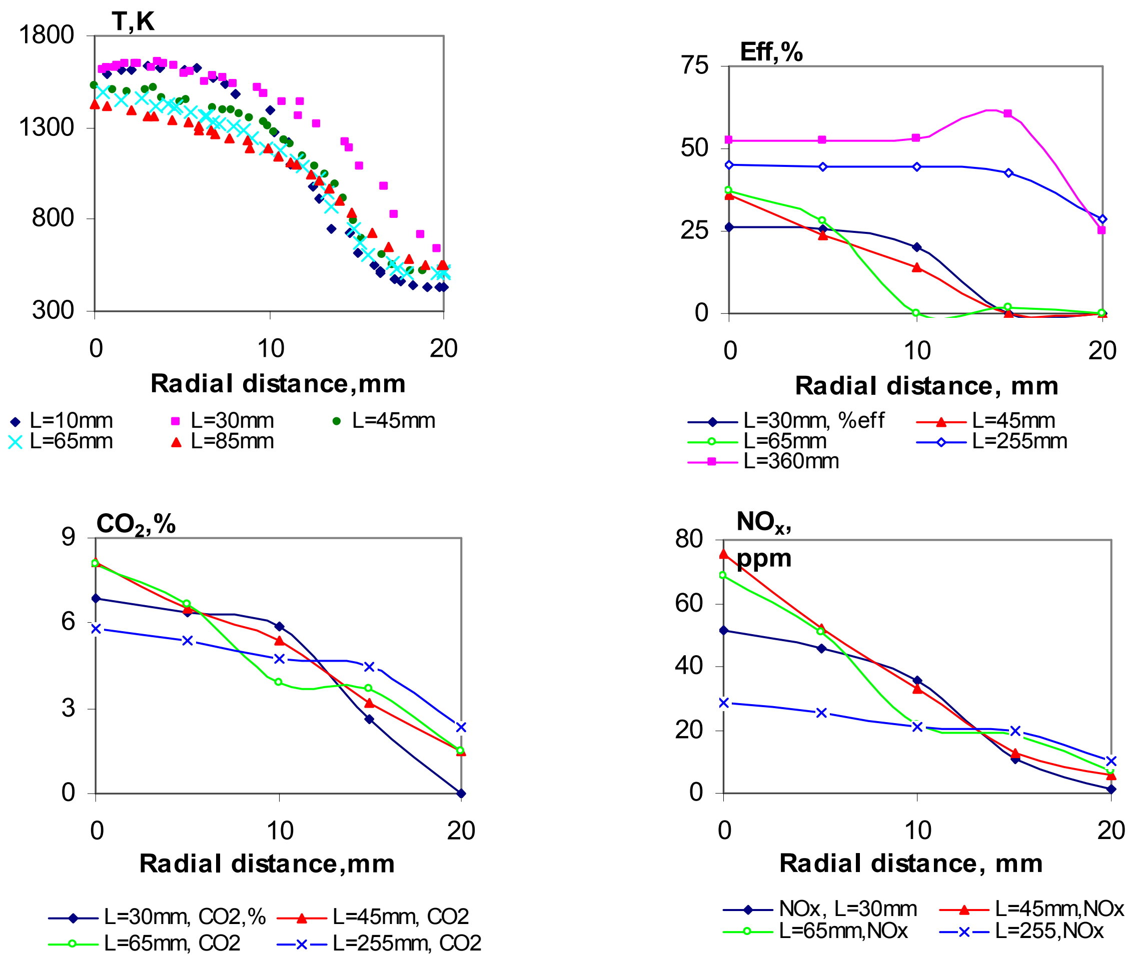


Figure 4. The formation of the undisturbed flame temperature and composition profiles downstream the flame channel flow.

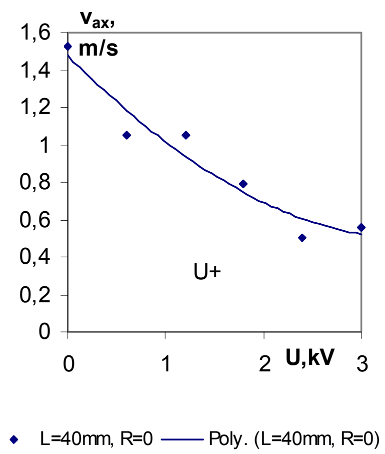


Figure 5. The electric field effect on the axial swirling flame velocity.

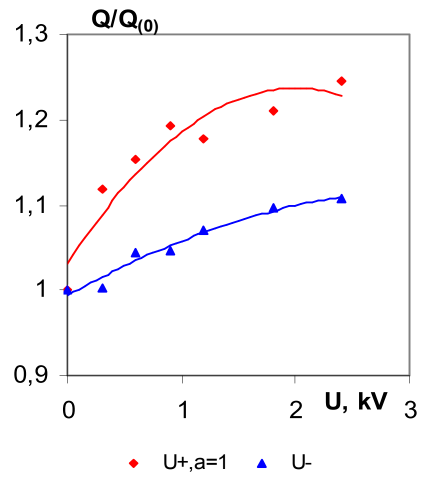


Figure 6. The electric field-enhanced variations of the heat production downstream the flame channel flow

In contrary to the electric field effect on the non-premixed swirling flame flow, for the conditions of the premixed swirling flame flow the field effect on the mixing and burnout of the flame compounds is less pronounced and dominates the field-enhanced variations of the radial heat transfer from the flame reaction zone to the channel walls (Fig.6.), promoting a cooling of the flame reaction zone with direct influence on the temperature and composition of the products. Moreover, the field-enhanced reverse axial mass transfer promotes penetration of the cold airflow from surrounding into a channel with swirling flame flow dilution. For such conditions close to the
channel outlet (L=340 mm) is fixed a slight decrease of the temperature and mass fraction of the main products (Fig.7.). It is interesting to note that for the positive bias voltage of the axially inserted electrode downstream the shear layer slightly increases mass fraction of NO_2 in the products (Fig.7.), indicating that the electric field promotes reactions that lead to the NO_2 formation, developing at the air excess in the flame reaction zone: $NO+O=NO_2$. Actually, the local measurements of the flame composition confirm that the field-enhanced penetration of surrounding air into the channel results in an increase of the air excess in the flame reaction zone that finally promotes the enhanced formation of NO_2.

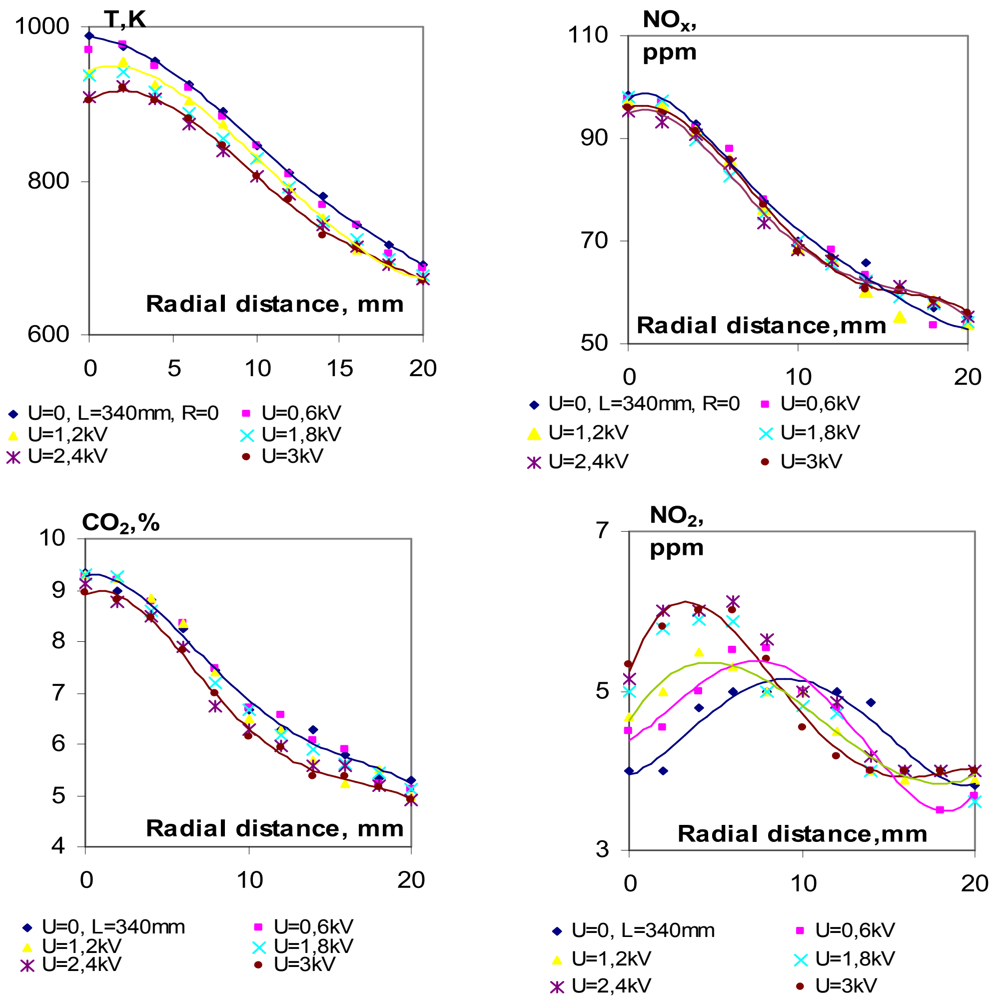


Figure 7. The electric field effect on the temperature and composition of the products at the channel outlet for the positive bias voltage of the axially inserted electrode.

References

1. D. Fang, J. Majdalani, Simulation of the Cold-Wall Swirl Driven Combustion Chamber, AIAA 2003-5055, 2003, pp.1-9.
2. K Gupta, M.J. Lewis, S. Qi, J. Goetz, M. Gupta, Effect of Swirl and Momentum Distribution on Thermal Non-uniformities and Emissions in Premixed Flames, ATSP-4, The Combustion Laboratory, University of Maryland, Dept. of Mechanical Engineering, 1997, pp.1-32.
3. Yiang Huang, Hong-Gye Sung, Shih-Yang Hsieh and Vigor Yang, Large-Eddy Simulation of Combustion Dynamics of Lean-Premixed Swirl-Stabilized Combustor, Journal of Propulsion and Power, Vol.19, No5, 2003, pp. 282-794.
4. M. Zaķe, I. Barmina, M. Lubāne, Swirling Flame, Part 1. Experimental Study of the Effect of Staged Combustion on Soot Formation and Carbon Sequestration from the Nonpremixed Swirling Flame, Magnetohydrodynamics, Vol. 40 (2004), No.2, pp. 161-181.
5. M. Zaķe, D. Turlajs, I. Barmina, G. Šteins, Influence of the Electric Field on the Swirling Flame Formation, Scientific Proceedings of Riga Technical University, Transport and Engineering, Vol.21, pp.94-101.

Barmina I., Turlajs D., Zaķe M., Liesmas virpuļplūsmas degšanas procesa dinamika elektriskā laukā

Ir veikti eksperimentālie pētījumi, lai noskaidrotu ārējā elektriskā lauka efektu uz iepriekš sajauktas liesmas virpuļplūsmas dinamiku ar mērķi veikt degšanas procesa un degšanas produktu sastāva kontroli. Pētījumu rezultāti ilustrē elektriskā lauka ietekmi uz siltuma un masas pārneses procesiem, kas nosaka liesmas virpuļplūsmas formu un izmēru, kā arī liesmas ātruma, temperatūras un degšanas produktu sastāva sadalījuma veidošanos un ir būtiski atkarīga no aksiāli ievietotā elektroda potenciāla un polaritātes. Rezultātu analīze liecina par turpmāko pētījumu nepieciešamību kaitīgo izmešu samazināšanai apkārtējā vidē ar degšanas procesu optimizācijas palīdzību.

Barmina I., Turlajs D., Zake . Electric field effects on the swirling combustion dynamics

The experimental study of the electric field effects on the swirling partially premixed flame combustion dynamics is carried out with the aim to provide control of the combustion efficiency and composition of the products. The results illustrate the electric field effect on the processes of heat and mass transfer, determining the swirling flame shape, size and also the formation of the flame velocity, temperature and composition profiles, depending on the bias voltage and polarity of the axially inserted electrode.Analysis of present situation shows necesserity for further investigations in field of flue gasses mitigation by means of controlled and optimal combustion processes.

Бармина И., Турлайс Д., Заке М. Влияние электрического поля на динамику горения закрученного потока.

Экспериментальные исследования по влиянию электрического поля на динамику закрученного, частично перемешанного пламени проведенны с целью контроля за эффективностью процессов горения и составом продуктов сгорания. Результаты исследования показывают влияние электрического поля на процессы тепломассопереноса, определяющего форму и размер закрученного пламени, а также на распределение профилей скорости, температуры и продуктов сгорания в зависимости от потенциала и полярности аксиально установленного электрода. Анализ результатов проведенных исследований показывает необходимость дальнейших исследований в области уменьшения количества вредных выбросов с помощью контролируемого и оптимального процесса горения.