THE ELECTRIC FIELD-FORCED FORMATION OF THE SWIRLING FLAME FLOW FIELD

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Introduction. The goal of the recent experimental study is to investigate the electric field effect on the flame dynamics and correlations between the field-enhanced variations of the swirling flame dynamics and the composition of the products with the aim to develop an active electric control of combustion and composition of polluting emissions. Previous investigations have shown that the electric field highly disturbs the swirling flame shape and length with direct influence on the combustion characteristics and composition of the products, depending on the bias voltage and polarity of the central electrode [1, 2]. The focus of recent investigations is the evolution of electric field effect on the swirling flame dynamics and velocity field formation, mostly determining the variations of combustion and emission characteristics.

1. Experimental set-up. The experimental studies of the field effect on the swirling flame dynamics are carried out both under the premixed and non-premixed combustion conditions, using two types of swirl burners [1, 2]. A premixed swirling burner is designed using the radial propane supply into the burner channel through six orifices of 1 mm diameter [1], while a non-premixed swirling burner [2] uses the axial propane supply through the fuel delivery tube (16 mm inner diameter), positioned coaxially to the annular swirling air supply nozzle (18 mm inner diameter and 26 mm outer diameter). The air swirl motion in these devices is imparted using the air swirler with eight tangential inlets of equal diameter (3 mm). Propane supply into the burner can be varied in a range from 0.3 l/min to 1 l/min, while the air supply ranges from 7 l/min up to 21 l/min. The investigations of the swirling flame velocity flow field formation downstream the flame channel flow are carried out using a Pitot tube, the formation of temperature field – using Pt – Pt/Rh (10%) thermocouples, while composition of emissions – using the gaseous analyzer Testo-350XXL. The investigations of velocity and temperature field formation are carried out downstream the flame channel of total length 100 mm, composed of five sections as long as 20 mm. The diagnostic probes into the flame channel flow are inserted through the orifices bored in the walls of these sections.

The investigations of the DC electric field effect on the flame velocity field, temperature field and composition of the products are carried out, using an axially inserted electrode. The bias voltage and polarity of the electrode relative to the channel walls and surface of the burner in these experiments can be varied in a range of -3 kV–$+3$ kV, while the ion current in these experiments is limited to 200 μA.

2. Results and discussion. The investigations of the non-premixed swirling velocity field formation for the cold conditions indicate that the peak value of the mean axial flow velocity is located close to the centerline of the fuel nozzle, while the peak value of the mean tangential velocity – close to the outlet of

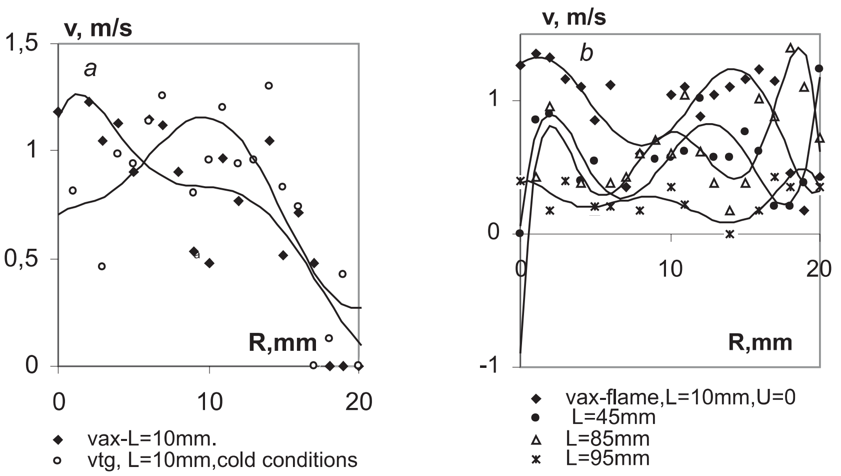

Fig. 1. Formation of the radial profiles of the axial and tangential velocity compounds for the cold conditions at the burner outlet (*a*) and formation of axial velocity profiles downstream the non-premixed swirling flame flow for the stoichiometric propane/air supply ($a \approx 1$) at the burner outlet (*b*).

the annular air nozzle (Fig. 1*a*). The swirl number (S) of the fuel/air mixture at the burner outlet for the given swirl burner geometry has been defined locally as a relation between the local values of the tangential and axial velocity compounds ($S \approx v_{\mathrm{tg}}/v_{\mathrm{ax}}$). Close to the burner outlet, the local value of swirl number varies in a range of $S \approx 1$, 0–4.5 with the peak value close to the exit of the annular air nozzle, so indicating the strongly swirled airflow formation. For the fixed geometry of the swirl burner and the fixed rate of fuel and air supply the common feature of flow patterns for the non-premixed swirling flame flow is the formation of the central recirculation zone extending up to $L = 90$ mm with an adverse pressure and reverse axial flow formation upstream to the burner outlet. Fig. 1*b* illustrates a typical axial flow field formation downstream this region for the non-premixed combustion conditions.

Fig. 1 shows that there are two peaks in radial profiles of the axial flame velocity – one close to the flame centerline and the other – close to the annular air nozzle (Fig. 1*b*). Close to the burner outlet – up to $L \approx$ 30–40 mm the mean axial velocity downstream the centerline of the swirling flame flow ($R = 0$) is positive, indicating that the axial fuel flow penetrates through the central recirculation zone, induced by the swirling motion of the air stream at the outlet of the annular nozzle. At this stage of the swirling flame flow formation the centrifugal body forces, associated with the air swirl, dump the turbulent mixing of the flame compounds, producing a relatively cold ($T \approx$ 800K) fuel-rich flame core, surrounded by a low-temperature annular reaction zone ($T \approx$ 1500K) [2] (Fig. 2*b*). As the main factor for $\mathrm{NO_x}$ formation during the propane combustion is the flame temperature, the formation of a low-temperature staged fuel combustion downstream the non-premixed swirling flame flow produces a low concentration level of $\mathrm{NO_x}$ in the products that does not exceed 40–50 ppm for $\alpha \approx$1.00–1.25. Further downstream the flame centerline the mean axial velocity of the fuel flow gradually decreases and actually stops as far as $L =$ 40–50 mm from the burner outlet (Fig. 2*a*). At this distance, the axial fuel flow from the burner outlet fully balances the reverse axial flow of the hot products, forming a stagnation point of the axial velocity compound. The axial fuel flow stagnation enhances the radial fuel flow motion and, therefore, promotes the turbulent mixing of the fuel flow with an air swirl, so enhancing the fuel burnout with radial expansion of the flame

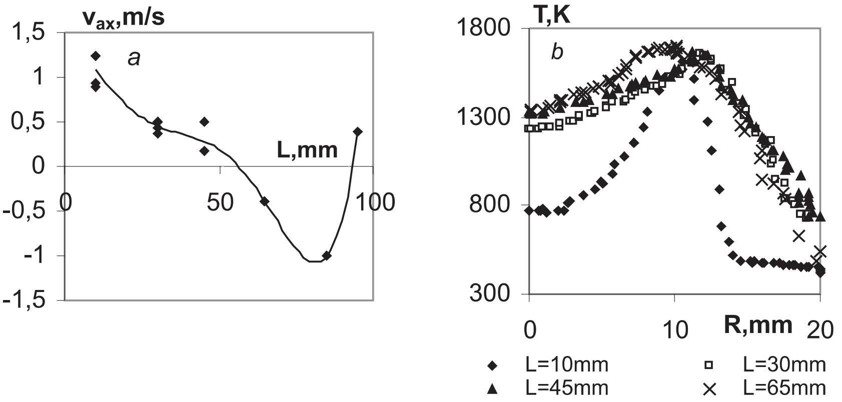

Fig. 2. Vvariations of the mean axial velocity (*a*) and swirling flame temperature profiles (*b*) downstream the central recirculation zone.

temperature profiles (Fig. 2*b*). In addition, the reverse axial motion of the hot products provides an additional heat supply from the annular reaction zone into the flame core, increasing the temperature downstream the flame centerline up to 1300–1400 K. Above the flame stagnation point ($L > 50$ mm) – up to the top of the recirculation zone ($L \approx 90$ mm) dominates the reverse axial motion of the hot products, determining the negative value of the mean axial velocity (Fig. 2*a*). Finally, the downstream flow field contraction is observed for $L > 95$ mm, where the mean axial velocity gradually changes from a reverse axial flow to a downstream flow (Fig. 2*a*).

The experimental study of the electric field effect on the swirling flame dynamics has shown that the electric force applied to the swirling flame flow highly disturbs the recirculation zone and the mean axial velocity profile, depending on the bias voltage and polarity of the central electrode. Consequently, the positive bias voltage of the central electrode produces more pronounced variations of the flame velocity field by enhancing the reverse axial motion of the positive ions and neutral gaseous species upstream to the burner outlet. By analogy with the effect of the swirl-enhanced reverse motion on the axial fuel flow formation, the field-enhanced reverse axial motion of the flame compounds gradually slows down the axial fuel flow downstream the flame core, highly disturbs the flame velocity field inside the annular reaction zone and promotes the axial flow formation along the outside part of the reaction zone (Fig. 3*a*, Fig. 4*a*).

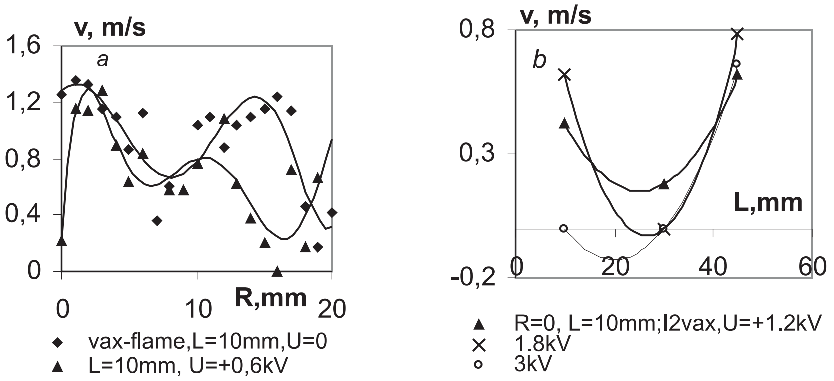

Fig. 3. Electric field-enhanced variation of the mean axial velocity profiles at the burner outlet (*a*) and field-enhanced variations of the mean axial velocity downstream the flame centerline (*b*).

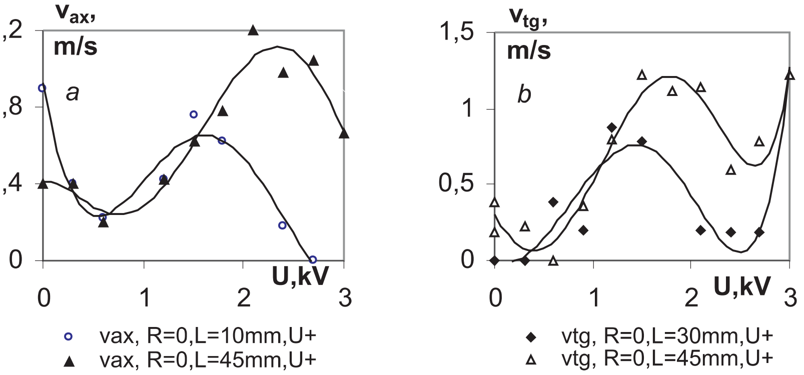

Fig. 4. Electric field-induced variations in heat loss from the gasifier ($Q1$) and flame of volatiles ($Q2$).

By increasing the positive bias voltage of the central electrode, the stagnation point of the swirling flame flow gradually shifts upstream the flame centerline to the burner outlet (Fig. 3*b*), while the swirl motion of the flame flow gradually approaches the flame centerline so enhancing swirl motion of the flame compounds inside the fuel-rich flame core. The peak of the tangential velocity (v_{tg}) inside the flame core is observed for $U \approx +1,2$–1,5 kV (Fig. 4*b*).

The previous experimental study of the electric field effect on the flame formation and composition of the products have shown [2] that, under this regime, the electric field-enhanced swirl motion results in an increase of residence time of soot growth, providing a more intensive soot formation downstream the fuel-rich flame core and mass growth of soot nanoparticles deposited on the surface of the central electrode. Moreover, the field-enhanced carbon sequestration results in a correlating decrease of the carbon burnout, decreasing the rate of heat release and temperature inside the flame reaction zone, so reducing carbon emissions by 10-15% and decreasing the rate of thermal NO production. In fact, the mass fraction of NO emissions inside the products decreases below 20 ppm. The more intensive NO_x production downstream the swirling flame flow is found for $U > 1.2$ kV, when the competitive process of field-enhanced mixing of the axial fuel flow with the air swirl enhances the fuel burnout, so increasing the flame temperature inside the flame downstream regions and mass fraction of NO in the products [1, 2]. Actually, the results presented above confirm the correlation between the field-enhanced variations in the flame dynamic and variations in the composition of the products. The results obtained could be helpful for optimization of operating conditions, using electric control of the flame dynamic with a correlating control of fuel combustion and minimizing environmental impact of fossil fuel combustion.

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