Electrical Control of Flame Carbon and Polluting Emissions from Fuel Combustion

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Abstract

The results of experimental investigations of electrical control of flame carbon from the sooting propane-air flame are presented. The results show that the processes of soot formation and carbon capture from the flame are greatly influenced by the flame structure, temperature levels and the local mass fraction of unsatured hydrocarbons in the flame. The DC electrical field enhanced mass transfer of hydrocarbons disturbs the spatial distributions of the temperature and mass fraction profiles along the flame channel flow with direct influence on the processes of fuel combustion, soot formation and carbon capture from the flame. The radial electric field effect on the processes of soot formation and carbon capture from the flame is studied by varying the bias voltage of the central electrode and equivalence ratio of the propane-air mixture

Introduction

The amounts of greenhouse gases, such as CO_2, N_2O, in the atmosphere steadily increases, as fossil fuels are used for power generation, transport and heat generation. Soot emission from flames and fires is a primary source of unwanted pollution and the process of soot formation is one of the key environmental problems associated with the operation of practical combustion devices for the oil industry and engine manufacturers. In contrast to the unwanted soot production from fuel combustion, soot production, as carbon black is important for many applications, like automobile tires, paints, printing and copier inks filters or as precursor for chemicals. With this in mind, the different techniques are developed to control the process of soot formation and, among them, the effects of AC and DC electric fields on soot formation are studied to perform the electric control of flame carbon [1-5]. These studies illustrate the there are contradictions of the electric field effects on soot formation and, depending on field strength, orientation and frequency, soot growth can be increased or reduced. Therefore, more detailed studies are needed to improve understanding the DC and AC field effects on soot formation, carbon capture and sequestration from flames.

It should be noted that the mechanisms that cause soot formation in flames are among the most important unresolved problems of combustion science as the formation of soot is the most complex chemical system in flames. In addition, the processes of soot formation, growth, and oxidation of soot particles in flames involve an interaction between chemistry and fluid mechanic. A great deal of information obtained over past years on soot formation has been summarised in [6,7]. First of all, soot begins to form in a high temperature environment at a critical equivalence ratio. Several researchers have reported the existence of a threshold temperature (between 1300K and 1600K) above which soot formation occurs in flames. Soot is most likely to be formed in fuel-rich conditions. A model of soot growth has been developed based on acetylene as the soot precursor using fundamental chemistry to describe the process of soot formation [8]. First, a small fraction of the fuel (propane,

methane, etc.) decomposes into hydrocarbon radicals who, under fuel rich conditions, form small molecule (C_2H_2) and reactive radicals of various sizes. Those species add hydrocarbon radicals for growth to form the first particles that consist of chainlike aggregates. Soot particles, containing several thousands of carbon atoms are formed within few microseconds [9].

Experiments involving soot formation in premixed conditions with different fuels show similar sooting tendency [10]. It is suggested that all fuels break down into the same species, which leads to soot growth. Such a species has been postulated to be acetylene, which builds up into ring structures to give a soot particle by polymerisation and cyclisation processes. In fact, the final particle size is determined by a decrease in the reactivity of the soot particles as they grow [11].

The investigations of the rates of soot formation and deposition on the electric field intensity allows to conclude that soot particles in flames are positively charged both by electron emission and by attachment of positive charge and, therefore, soot growth can be manipulated by the electric fields [1,2]. The investigations of soot growth confirm that some of intermediate species that lead to the soot formation are electrically charged, determining the positive charge of the soot particle [12]. One possible route of soot growth via ions can be expressed as a result of reactions: $CH+C_2H_2 \rightarrow C_3H_3^+$; $C_3H_3^+ + C_2H_2 \rightarrow C_5H_5^+$; $C_5H_5^+ + C_2H_2 \rightarrow C_6H_5.CH_2^+$, etc. The investigations of the DC electric field effect on propane-air flame have shown that the electric force acting on flame, enhances ion drift motion in the field direction by varying the spatial distribution of intermediate charged species [4,5]. Hence, the electric field disturbs the local equilibrium of reactions that lead to fuel combustion and soot growth via ions, depending on the bias voltage and equivalence ratio of fuel-air mixture. In addition, the radial DC field-enhances transfer of soot precursors to the negatively biased central electrode that produces the local variations of soot growth by varying the carbon capture and sequestration from the flame. The main objectives of present investigations are to study the radial field effects on local characteristics of sooting flame with the aim to perform electric control of the processes, determining soot growth and carbon capture from the flame. Results pertaining to evolution of the processes in sooting flame and the radial electric field effects on the processes of soot growth and carbon capture from the flame are presented.

1. Experimental

The current research is conducted in the partially premixed propane-air flame using experimental set-up that includes a burner, sectioned water-cooled channel and cylindrical electrode of length L=250mm. The electrode is aligned along the flame core up to the exit of water-cooled channel. The bias voltage of the central electrode is varied in the range 0 to -3kV with subsequent variation of the ion current in the range $0-3.10^{-4}$ A. The radial electric field is formed in the space between the central electrode and the supporting channel walls. The water-cooled channel is composed of three water-cooled sections with the diagnostic sections between them. The diagnostic sections have the peepholes that allow inserting the diagnostic tools- probes and thermocouples (Pt/Pt-Rh) into the flame flow. These probes can be moved across the flame to study the radial and axial distribution of the flame temperature and composition and the radial electric field effects on the spatial distribution of the flame parameters (Fig.1). To obtain the spatial distribution of flame composition and the relative mass fractions of the flame compounds, local gaseous samples are extracted from the flame flow by using microprobe technique. These samples are analysed by absorption spectroscopy in the range 2-15 mμ. The spatial distribution of the flame radiative emission is studied in the visible spectrum range- from 400 to 600 nm.
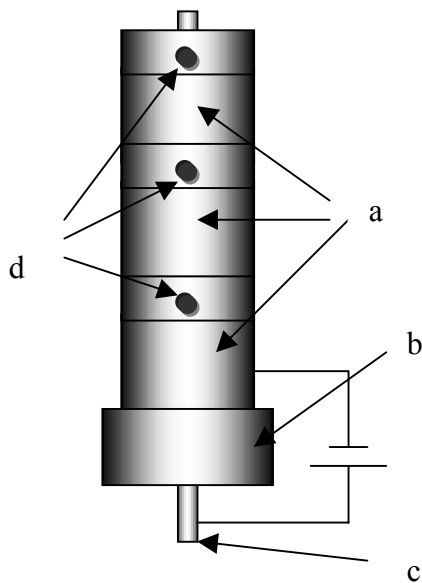
Fig. 1. Schematic drawing of the experimental set-up. a) water-cooled channel sections, b) burner, c) central electrode, d) peepholes for inserting the diagnostic tools into the flame flow.

The electric field effect on soot formation and carbon capture from sooting flame is estimated from the local measurements of the flame temperature, composition, radiation and weight increase of the deposited soot coatings on the surface of negatively biased electrode. The investigations are carried out by varying the equivalence ratio of the propane-air mixture in the range from $\alpha=0.3$ to $\alpha=1$.

2. Results and Discussion

The preliminary studies along the free undisturbed propane flame flow are conducted in order to evaluate the processes that lead to soot formation for fuel-rich conditions. These studies confirm that the process of soot formation can be entirely related to propane decomposition during oxidation at the initial stage of the free flame formation with resulting increase of the mass fraction of soot precursors- methane and acetylene (CH_4, C_2H_2) in the flame reaction zone. For fuel- rich conditions ($\alpha \approx 0,3-0,5$) the dominant propane decomposition develops at the distance L<30 from the exit of the burner. The maximum value of the mass fraction of soot precursors (C_2H_2, CH_4) in the flame core is achieved at a distance L$\approx$20-30mm from the exit of the burner (Fig.2). At this critical distance the axial temperature of premixed propane-air flame and the mass fraction of CO_2 drops to the minimum value (Fig.3). Further development of the temperature and mass fraction profiles and the processes that lead to soot growth for fuel-rich conditions can be related to diffusion flame appearing downstream, in which CO oxidises to CO_2.
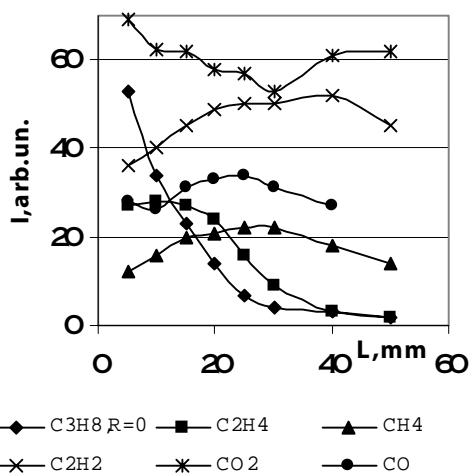

Fig.2. The axial distribution of the flame compounds along the free propane-air flame flow.

For fuel-rich conditions ($\alpha<1$) the process of soot formation begins with homogeneous nucleation of reactive hydrocarbon radicals and small acetylene molecules in the gas phase [13] that is initiated at L$\approx$30mm and condense chemically to form the first particles. During growth of first chainlike aggregates the density of soot precursors along the flame flow reduces. The most intense reduction of the mass fraction of soot precursors is observed at L>30mm (Fig.2). The dominant soot growth develops along the flame core (R<10mm) in which the temperature exceeds the threshold temperature of soot formation - T=1300-1550K (Fig.3).
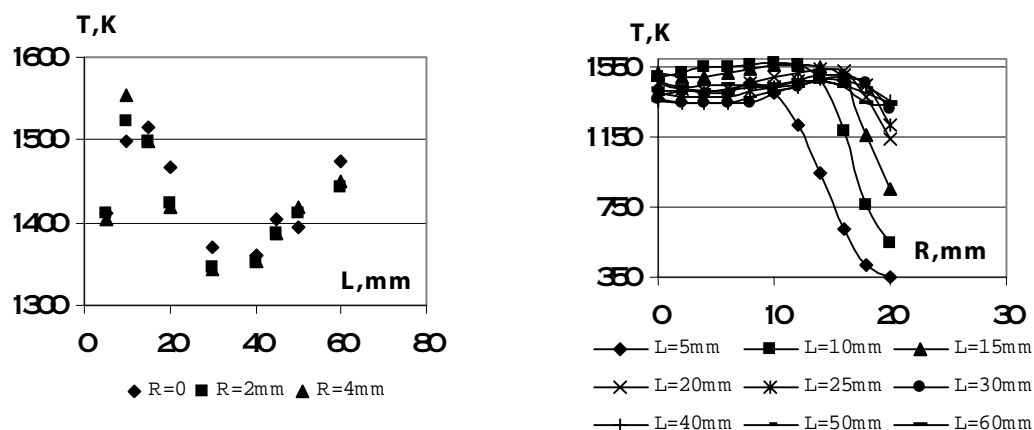
Fig.3. Radial and axial distribution of the temperature for the premixed fuel-rich propane-air flame channel flow (α=0.45).

The growth of soot particles flame is invariably accompanied by yellow luminous emission of the reaction zone that is due to continuos emission of soot particles and contribution of band emission ($^3\Pi \rightarrow {}^3\Pi$) of C_2 radicals in a range of $\lambda \approx 550-570$ nm [10] (Fig.4). Since first ultrafine soot particles (d=0.02-0.7 μm) are considered to be non-scattering and absorbing ($\pi d/\lambda \ll 1$), an increase of the volume concentration of the soot particles leads to attenuation an destruction of band emission of hydrocarbon radicals (C_2 and CH) in the UV and visible spectrum regions. The attenuation of band radiation of hydrocarbons depends on the volume concentration of the soot particles (C) and can be approximated as $k_\lambda \approx Ck/\lambda$ (here k is a constant). Therefore, as band emission of hydrocarbons is attenuated, the dominant increase in luminosity along the flame core can be attributed to soot radiation.
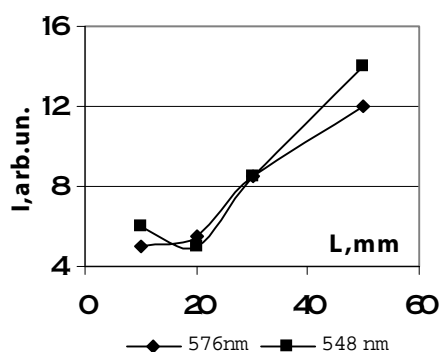

Fig.4. The axial variation of the flame emission during the growth of the soot particles.

Similar process of soot formation develops along the partially premixed flame channel flow that is followed by soot deposition on the surface of the central electrode. For the conditions of stoichiometric and undisturbed flame flow (α=1,U=0) the rate of soot formation and deposition is quite small and can be increased by increasing the equivalence ratio (α) of the burner exit flow and fuel excess in the propane-air mixture [4] (Fig.5).
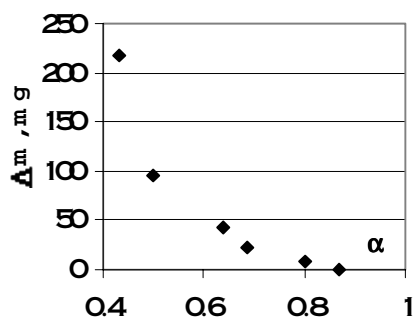

Fig.5. The effect of fuel excess on soot deposition on the central electrode along the flame channel flow.

By subjecting the flame to the electric field, the field-forced ion drift motion and momentum transfer from ions to gaseous compounds enhances the radial mass transfer of hydrocarbons. Consequently, the field-enhanced heat/mass transfer modifies the flame

structure, disturbs the temperature and mass fraction profiles of the flame compounds and causes a local increase of fuel excess at the vicinity of the central electrode with feedback influence on the rate of soot growth and deposition. In addition, the field-enhanced ion transfer to the central electrode promotes soot formation via ions, as increases the density of ions in a near vicinity of the electrode [5]. The dominant field-enhanced soot formation and deposition is observed in a limit of the weak fields and for the negatively biased central electrode (Fig 6). From Fig.6 it follows that in this limit the mass growth of the deposited soot particles increases up to the peak value that is observed at U≈1.8 kV and then reduces, as the bias voltage is increased.
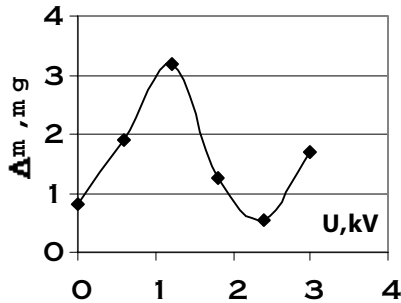

Fig.6 The electric field effect on soot deposition on the surface of the negatively biased central electrode by increasing the negative bias voltage.

Depending on the negative bias voltage, the field-enhanced soot formation reduces the mass fraction of soot precursors (C_2H_2) that is observed at the near vicinity of the central electrode (R=0-2 mm) (Fig.7).
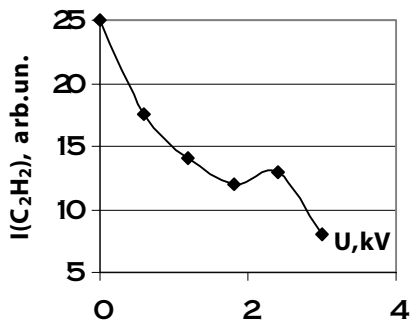

Fig.7. The electric field-enhanced variations of the mass fraction of soot precursors.

In addition to the field-enhanced soot growth, the field-enhanced soot deposition results in decarbonization of fuel-rich flame flow by reducing the amount of carbon to be burned along the flame core. Hence, reduces the heat release from fuel combustion, temperature of the reaction zone, as well as the temperature and the mass fraction of CO_2 and CO in the products (Fig.8).
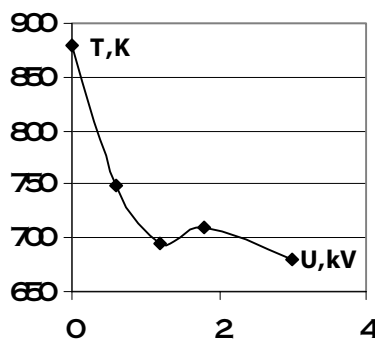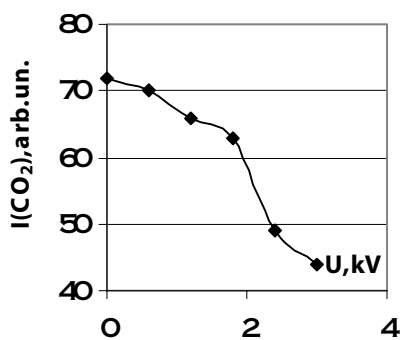

Fig.8. The radial electric field effect on the temperature and mass fraction of CO_2 in the flame core at the exit of the water-cooled channel.

As the bias voltage of the central electrode is increased (U>1.8 kV), the temperature of the reaction zone falls below the threshold temperature of soot formation (T<1300K). Therefore, the rate of soot growth at the vicinity of central reduces by reducing the amount of soot that is deposited on the collecting surface. In addition, the field-enhanced mass transfer of hydrocarbon radicals to the negatively biased electrode reduces the critical mass fraction of soot precursors and soot growth along the flame core. Results show that for such conditions reduces the intensity of flame luminosity in a visible spectrum range [4]. Therefore, in the limit of strong fields the reverse field effect on soot formation is observed

and in this limit the field effect on sooting flame can be used to eliminate the soot growth and deposition from fuel combustion.

Conclusions

Experimental investigations of soot formation and carbon capture from the flame demonstrates following:

Propane destruction and formation of soot precursors- CH_4, C_2H_2 along the flame core initiates the process of soot formation for fuel-rich conditions. The process of soot growth is followed by reducing the mass fraction of soot precursors in the reaction zone, attenuation of band emission of the flame compounds and by increasing the yellow luminosity of flame.

The field-enhanced mass transfer of hydrocarbons to the negatively biased electrode in the limit of week fields leads to the local increase of fuel excess at the vicinity of the electrode that provokes soot growth and deposition. In this limit the radial electric field effect on a flame can be used to perform the more intense carbon capture and sequestration from the flame. For strong fields the field-enhanced local variations of the temperature and mass fraction of soot precursors confines the process of soot growth and the field effect on the flame can be used to confine the processes of soot growth during the fuel combustion.

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