FUEL-AIR RATIO INFLUENCE ON MIXING PROCESSES BETWEEN PREMIXED ACETYLENE FLAME AND SURROUNDING AIR

by

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In this paper, the mean velocity, turbulence intensity and temperature profiles in different cross-sections of premixed acetylene flame and for different air/acetylene ratios are given. For velocity measurements laser-Doppler anemometer was used, while the temperature field measurements were performed by Pt-PtRh 10% thermocouple. LDA measurements and conditional and unconditional statistics of the velocity fluctuations produced by combustion products and surrounding air, can give more detailed data about the character and intensity of turbulent mixing in the flame. By comparative analysis of the obtained mean velocity and temperature profiles, length and width of characteristic regions of the premixed acetylene flame and their characteristic properties were established for different fuel-air ratios. With the increase of acetylene content in the mixture, velocity and temperature fields are considerably changing.

Introduction

Experimental investigations have been mostly performed with the industrial burners using laser-Doppler anemometry for velocity measurements and thermocouples for temperature measurements, with the aim to reduce noise and to increase combustion efficiency. In the several experimental studies [1–3], flow field of the premixed acetylene flame was analyzed. In experiments [3], according to the LDA-velocity information, different regions of the flow field of premixed acetylene-air flame have been established: the region of the flame front, the region of constant flame width (velocity), the developing region and the fully developed jet flow region. In experimental investigation by [4], using conditional and unconditional LDA statistics, entrainment process of the surrounding cold air into the premixed acetylene-air flame in these four characteristic regions was analyzed and mixing factor Ω as a measure of intensity of this process was established.

Matović *et. al.* [3], also analyzed changes of the premixed acetylene-air flame flow characteristics, which are caused by changes of conditions at the burner exit, changing exit velocity profiles and/or different fuel concentrations, analyzing only data obtained by LDA measurements. In this paper, the influence of different air/acetylene ratios on the length and width of characteristic regions and characteristic properties of the flow field is analyzed, using conditional LDA measurements and temperature measurements performed by using Pt-PtRh10% thermocouple. Mean velocity, turbulence intensity and temperature profiles have been measured at different cross-sections for different air/fuel ratio, $\lambda = 1$, $\lambda = 0.798$ and $\lambda = 0.630$. Intensity of turbulent mixing in different flame regions, was also discussed.

Experimental equipment and flow conditions

The experimental apparatus used in this study has been the same as in Bakić and Oka [4]. Uniform acetylene-air mixture with different air/acetylene ratio, $\lambda = 1$ (stoichiometric ratio), $\lambda = 0.798$ and $\lambda = 0.630$, but for the same volume rate, was supplied to the burner. The burner is consisted of a long pipe, with the 8 mm inner diameter and the length of 80 D. At the exit of the burner, fully developed turbulent velocity profiles were formed with mean velocity U_{av} = 15.45 m/s, Re ≈ 7800 and constant turbulent intensity around the burner axis (6%), with increase towards the rim (11%). The laminar burning velocity S_L for stoichiometric ratio ($\lambda = 1$), was estimated to be 1.83 m/s, therefore u_{rms}/S_L was 0.655. For this exit flow conditions shape of the flame was a nearly cylindrical "flame brush". This flame is considered to be within the wrinkled laminar region [5, 6]. Increasing of the acetylene content ($\lambda = 0.798$ and $\lambda = 0.630$) in the acetylene-air mixture changes the laminar burning velocity S_L. Visual observation of the flame front for the mixtures $\lambda = 0.798$ and $\lambda = 0.630$ indicates that the flame keeps cylindrical "flame brush" form and stays in the wrinkled laminar region.

Velocity measurements have been carried out using one-component laser-Doppler system consisting of a 15 mW helium-neon laser, a conventional transmission optics including a beam splitter and a double Bragg cell. All measurements have been carried out with a frequency shift of 5 MHz with long time stability of $10e^{-7}$ Hz. The premixed acetylene-air mixture and surrounding air were seeded with Al_2O_3 particles with mean diameter of 2 μm. Using the estimates given in Durst *et. al.* [7], it can be shown that 2 μm particles can follow the frequencies up to 3 kHz. An angle of 9° was chosen between the axis of the transmission optics and the axis of the receiving optics. With this optical arrangement dimensions of measuring control volume were 0.16×0.16×1.39 mm. At each measuring point, 7500 instantaneous velocity samples were recorded and were employed to compute the local mean velocity and turbulence intensity.

Uncoated thermocouple of Pt-Pt/Rh 10%, with a diameter of 100 μm was used for temperature measurements. The thermocouple was about 80 diameters long to minimize heat conduction. Radiation correction was performed according to Bradley and Matthews [8] and Stroomer [9].

Experimental results

Mixing in different regions of the premixed acetylene-air flame

Results of the mean velocity measurements along the flame axis, for the air/acetylene ratio $\lambda = 1$ and for conditional statistics are shown in Fig. 1. The axial velocity U_m is normalized by exit velocity at the jet axis $U_0 = 17.83$ m/s. Figure 1 clearly shows characteristic regions in the premixed acetylene flame: region of flame front, region of constant axial velocity, developing region and fully developed jet flow region. Characteristics of these regions were explained by Matović *et. al.* [3], Bakić and Oka [4].

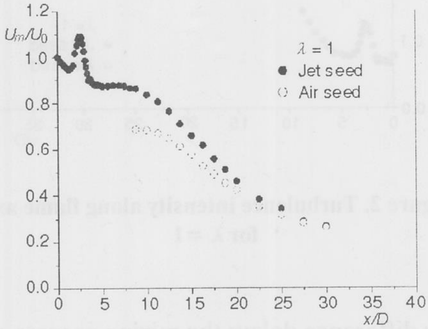

Figure 1. Mean velocity along the flame axis for $\lambda = 1$

The region of flame front ends approximately 3 *D* downstream of the burner exit. This region is characterized by sharp increase in axial velocity followed by velocity decrease. Rapid temperature increase caused by combustion brings a stream flow relaminarization downstream of the flame front and formation of the constant velocity region. Adiabatic temperature of premixed acetylene-air flame is about 2950 K. Our former experimental investigations, [10] and [4] have shown that constant velocity region downstream of the flame front is a sort of "potentional core".

The region of constant velocity ends about 8.5 *D* downstream of the burner exit. Measurements conditioned on the surrounding air could not been carried out for axial distances $x/D \leq 8.5$. In this region, fluid originating from the surrounding air does not penetrate toward the flame axis.

For axial distance $x/D = 8.5$ contribution to the mean axial velocity of the fluid originating from the jet is considerably higher than the contribution of the fluid originating from the surrounding air. Large eddies of entrained cold air have much higher density and thus greater inertia than the eddies of combustion products. The eddies in the flow are continually breaking down into the smaller eddies, while diffusion is taking place, at molecular level, at all eddy boundaries. The jet becomes fully turbulent in the region of sharply increasing turbulence, while the eddies of surrounding air continue to be engulfed into flame, further reducing velocity and temperature.

Turbulence intensity distribution along the flame axis for conditional seeding, shown in Fig. 2, has been normalized using local mean velocity at the axis. Just downstream the burner exit, turbulence intensity is approximately constant, until the flame front is reached. At the flame front, the maximum turbulence intensity occurs at the same point where the mean axial velocity has maximum value. In the measurement volume of

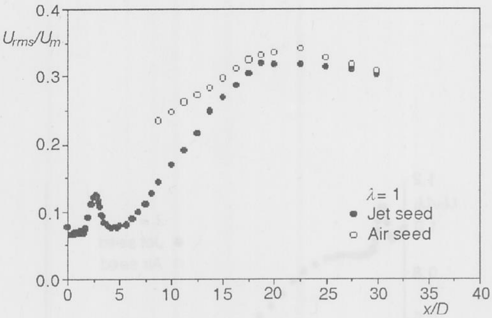

Figure 2. Turbulence intensity along flame axis for λ =1

LDA alternately are present reactants or products, which have different velocities leading to the increase of turbulence in the flame front. This can be seen from the change of the *pdf*(*u*) diagrams along the flame axis (see [10], [4]). After the sharp increase at the flame front, turbulence intensity considerably decreases in the constant velocity region. Increase of the turbulence intensity downstream of the constant velocity region occurs at the point where the eddies of air entrained from the flame surroundings have finally reached the flame centerline. Intensive mixing process between combustion products and surrounding air starts at this cross-section. Obviously, large density difference delays the mixing process, with downstream increase of turbulence intensity and intensification of mixing process. Detailed analysis of mixing process between premixed acetylene flame and surrounding air, in different regions of premixed acetylene-air flame, has been given in our earlier paper [4].

Axial mean velocity profiles in cross-sections $x/D = 5$, 8, and 10 for mixture with $\lambda = 1$ and conditional seeding are shown in Fig. 3, where y is distance from the flame axis. The mean axial velocity in the cross-sections $x/D = 5$ and 8 for conditional jet seeding has constant values for radial distances $0 \leq y/b \leq 0.6263$ ($y = 6$ mm), where b is distance from flame axis where axial mean velocity has value equal to the half of the velocity at the flame axis obtained by jet seeding. In this region there is no mixing between combustion products and surrounding air. Two mentioned cross-sections are in the region of constant velocity.

Decrease of the mean axial velocity in cross-section $x/D = 5$, for conditional jet seeding starts at the point where the mixing process begins. At axial distance $x/D = 8$ width of the region of constant velocity is less than at distance $x/D = 5$. The mixing processes between flame and surrounding air starts at $y/b = 0.3$ ($y = 3$ mm) from the flame axis. The shape of the velocity profile is similar to the velocity profile at the $x/D = 5$. Mean axial velocity profiles at axial distance $x/D = 10$ have the shape characteristic for fully developed region of an isothermal jet. At this distance does not exist the constant velocity region. This region was finished at the distance $x/D \approx 8.5$ what is obvious from Fig. 1.

Axial mean velocity, turbulence intensity and isotherms for different air/acetylene ratios

Mean velocity and turbulence intensity along the flame axis, for the three different air/acetylene volume ratios are show in Figs. 4 and 5. With the increase of acetylene share in the mixture above the acetylene share for stoichiometric conditions, velocity maximum that corresponds to the outer edge of the flame front is moving downstream and the lenght of the "flame brush" increases. This was also noticed by visual observation. Downstream of the flame front the velocity in the flame axis increases with the increase of acetylene content in the mixture. For the stoichiometric air/acetylene ratio $\lambda = 1$, theoretically complete combustion of reactants (acetylene and oxygen from air) can be obtained. The increase of velocity in the region of the constant velocity can be explained by the fact that the excess of acetylene that has not been burned in the flame front, ulteriorly burns up at the flow edges, using oxygen from surrounding air as reactant, causing the increase of the temperature in this region and decrease of the mixing intensity between the flame and surrounding air. This can also be seen on the radial temperature and mean velocity profiles. Length of the constant velocity region increases with the share of acetylene in the mixture. For the stoichiometric ratio $\lambda = 1$ the constant velocity region is long $x/D \approx 8.5$ distance, while for the ratio $\lambda = 0.798$ the length of the region is $x/D \approx 11$ and for $\lambda = 0.630, x/D \approx 13$.

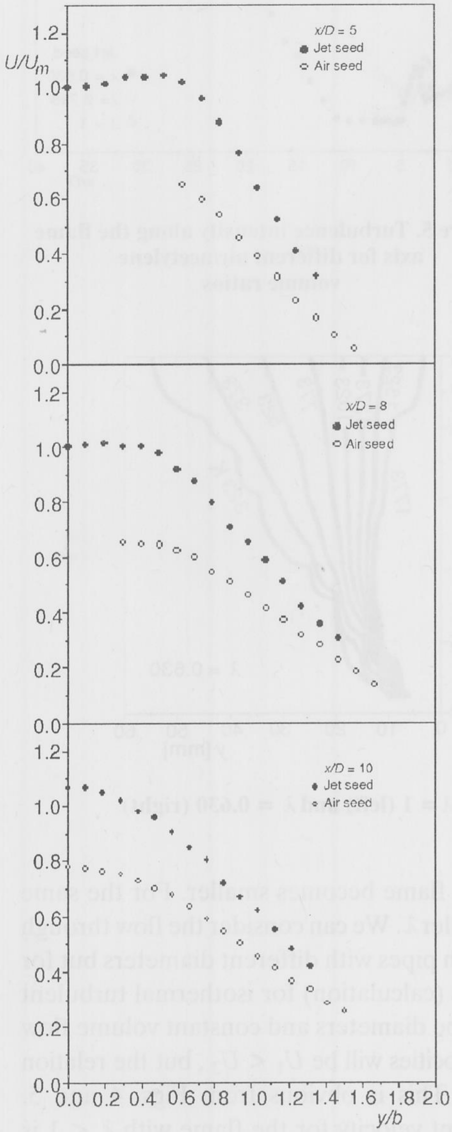

Figure 3. Profiles of mean velocity for flame with λ = 1 and conditional seeding at the distances *x/D* = 5, 8, and 10

With the larger share of acetylene in the mixture, the high temperature region at the edge of the flame is extended to the larger axial distance along the flame axis. Flame with a larger share of acetylene does not expand so fast as the flame with a smaller share of acetylene. This can be noticed in Fig. 6, where the flame isotherms for the stoichiometric air/acetylene ratio and for larger share of acetylene ($\lambda = 0.630$) are given.

Because of the more intensive combustion at the edges of the flame, temperature at the edges of the flame increases and leads to the decrease of mixing intensity between combustion products and surrounding air. At the same time, decrease of mixing intensity between combustion products and surrounding air leads to the slower spreading of the flame, for mixture ratios $\lambda < 1$. Volume

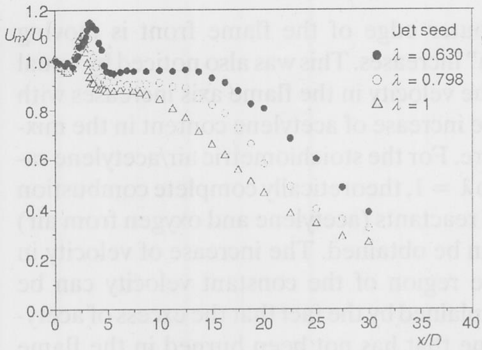

Figure 4. Mean velocity along the flame axis for different air/acetylene volume ratios

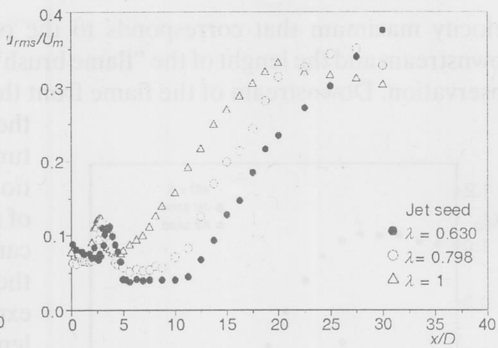

Figure 5. Turbulence intensity along the flame axis for different air/acetylene volume ratios

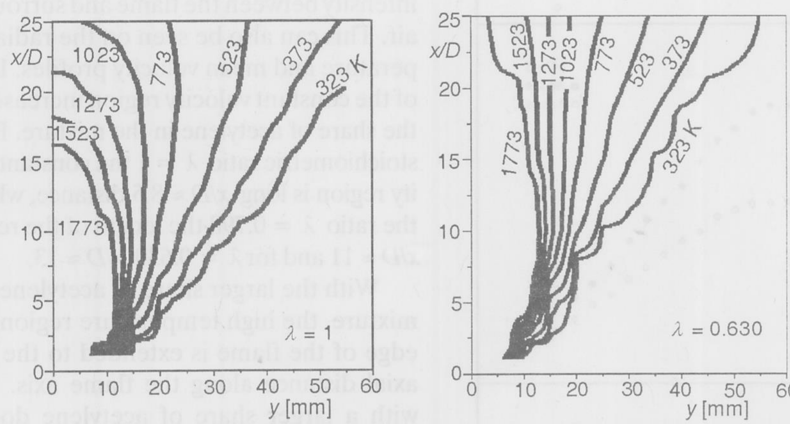

Figure 6. Isotherms for air/acetylene ratios $\lambda = 1$ (left) and $\lambda = 0.630$ (right)

gas flow rate rests constant but the width of the flame becomes smaller. For the same reason velocity at the flame axis increases for smaller λ. We can consider the flow through the region of constant velocity as the flow through pipes with different diameters but for the same volume flow rate. Very simple analysis (calculation) for isothermal turbulent flow through the pipe shows that for different pipe diameters and constant volume flow rate, ($Q_1 = Q_2$, $D_1 > D_2$, $\mathrm{Re}_1 > \mathrm{Re}_2$), mean velocities will be $U_1 < U_2$, but the relation between turbulence intensities is $u_{rms1} > u_{rms2}$. This is obvious from Figs. 4 and 5. Turbulence intensity in the region of the constant velocity for the flame with $\lambda < 1$ is smaller than turbulence intensity in the same region for the flame with smaller acetylene share. In our previous paper [4], by analyzing processes in the region of constant velocity, we have concluded that this region behaves similarly as the "potential core" of an isothermal jet, but from present analysis this region can be treated as turbulent flow in pipe. From this simple analysis we can conclude that relaminarization behind flame front is not complete.

Radial profiles of the axial mean velocity and temperature for different air/acetylene ratios

Figure 7 compares the mean axial velocity and temperature radial profiles at x/D = 5, 8, 10, and 15 distances for different air/acetylene ratios in the mixture. In the same cross-sections and for different air/acetylene ratios in the mixture, radial profiles of axial mean velocity are considerably different. At x/D = = 5 distance, increase of the velocity from the flame axis to the flame edges is noticeable. For stoichiometric ratio, $\lambda = 1$, mean axial velocity profile is nearly flattened up to y = 6 mm distance, because of the lack of mixing process between jet and surrounding air in this region. Increase of the acetylene content in the mixture leads to incomplete burning of acetylene in the flame front. The excess of the acetylene is burning further at the point where jet and surrounding air are starting to mix, which causes temperature increase in this area. Surrounding air serves as an oxidant for burning of the excess of acetylene at the flame edges. Temperature increase causes a velocity increase and leads to the occurrence of maximum velocity at the flame edges. In this area temperatures were above thermocouple measuring range. Increase of the acetylene content in the mixture causes increase of mean temperature radial profiles gradient. At the x/D = 8 distance, there is no more velocity maximum, because the greatest part of the acetylene is burned upstream from this cross-section. Constant velocity region spreads with the increase of the acetylene content in the mixture. At the x/D = 10 distance, constant velocity region in radial profile for $\lambda = 1$ and $\lambda = 0.798$ volume ratios does not exist, while for $\lambda = 0.630$ volume ratio at this distance it is still noticeable. Mean velocity profiles at the x/D = = 15 distance do not show existence of a constant velocity region for all three air/acetylene ratios.

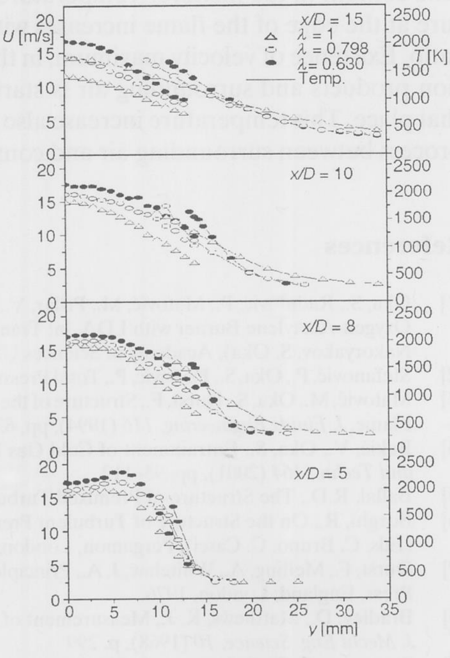

Figure 7. Radial velocity and temperature profiles at the axial distances x/D = 5, 8, 10, and 15

Conclusions

Temperature and velocity field measurements in the acetylene premixed flame for different air/acetylene ratios show that with the increase of acetylene content in the mixture, velocity and temperature fields are changing considerably. Velocities in the flame front region and in the whole flow field are increasing with the increase of acetylene content in the mixture.

Length of the constant velocity region increases with the increase of the acetylene content in the mixture. Temperature measurements have shown that the temperature at the edge of the flame increases with the increase of acetylene content in mixture ratio. Existence of velocity maximum, in the area where mixing process between combustion products and surrounding air is starting, is a result of acetylene excess burning at that place. This temperature increase also causes a decrease of the intensity of the mixing process between surrounding air and combustion products.

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