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FLOW FIELD OF TURBULENT PREMIXED ACETYLENE FLAME

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Abstract. *In this paper the profiles of mean axial and radial velocity components, turbulence intensity, Reynolds stresses* $\overline{uv}$, *probability density functions of velocity and mean temperature field in different cross-sections of premixed acetylene/air mixture with stoichiometric ratio are given. The velocity field measurements were performed with the one component laser-Doppler anemometry, while for the temperature field measurements Pt-PtRh10% thermocouple was used. Based on the velocity field measurements, for three different particle seeding points 1) in premixed unburned reactants only, 2) in surrounding air only, and 3) in both reactants and surrounding air, the contributions of different parts of the flow field and mixing processes between surrounding air and combustion products in characteristic regions of premixed acetylene flame were analyzed.*

1. INTRODUCTION

The development of turbulent reacting flow models has proven to be difficult due to a limited understanding of the effects of turbulence on combustion process. Laser-based diagnostic technique for velocity measurement [1-4], temperature and species concentrations [5,6], provide more data needed to verify current and to develop new turbulent models.

Experimental investigation of cold gas entrainment into thermal plasma [7] and into non-premixed propane jet [8] has shown that large difference of density between the hot gas flow and surrounding air is responsible for the delay of mixing process, but afterwards lead to the increase of turbulence level. Application of conditional and unconditional sampling techniques to turbulence research has often been used in experiments. Original application of conditioning is for discriminating between turbulent

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and irrotational fluid elements in nonreacting free turbulent shear flows [9-12] between reacting turbulent flows and coflowing air stream [3,8], and between burnt products and unburnt reactants in premixed conical turbulent flame [13]. In our earlier experiments [1], four characteristic regions of premixed acetylene flame mean flow field have been established: (I) region of the flame front, (II) region of the constant flow velocity, (III) the developing region and (IV) fully developed jet flow region, Figure 1. Characteristic changes of the mean velocity field of the premixed acetylene flame and surrounding air in these characteristic regions are analyzed in this paper.

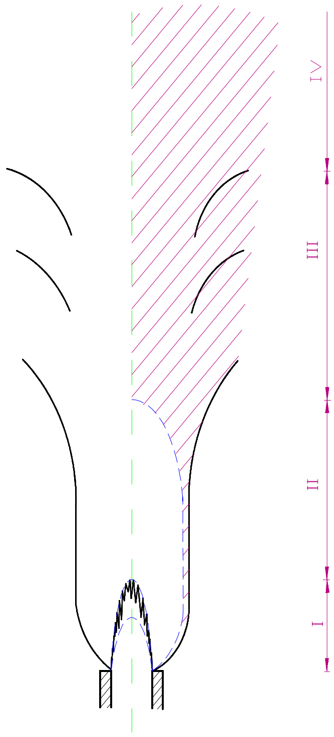

Figure 1. Flow field of premixed acetylene flame.

The results of LDA measurements for three different particle seeding points 1) in premixed unburnt reactants only, 2) in surrounding air only (conditional seeding), and 3) in both reactants and surrounding air (unconditional seeding), show that this seeding technique provides a useful marker for fluid originating from the combustion products and surrounding air.

Based on a mean temperature field measurements with the Pt-PtRh10% thermocouple, it was possible to obtain complete picture of the flow field in premixed acetylene flame.

2. EXPERIMENTAL EQUIPMENT AND FLOW CONDITIONS

The experimental apparatus used in this study has been the same as in [1], except for the new burner with 8 mm inner diameter. Uniform acetylene/air mixture with stichiometric ratio was supplied to the burner. At the exit of the burner, fully developed turbulent velocity profiles were formed with mean velocity $U = 15{,}45$m/s and $\mathrm{Re} = 7860$. Measurements carried out at the burner exit have shown that the turbulence was constant around the burner axis, with slight increase towards the rim. 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. Instantaneous velocities in the axial and radial directions have been measured at the same point by rotating the LDA optics for 90 degrees.

The fuel and surrounding air were seeded with Al_2O_3 particles with mean diameter of 2 µm. Using the estimates [15], it can be shown that 2 µm particles can follow the frequency up to 3 kHz. Uncoated thermocouple of Pt-Pt/Rh 10% , with a diameter of 100 µm was used. The thermocouple is about 80 diameters long to minimize heat conduction. Radiation correction is performed according to [18].

3. EXPERIMENTAL RESULTS

3.1. Axial mean flow velocity, turbulence intensity and temperature profiles

Results of mean velocity measurements along the flame axis, for conditional and unconditional statistics are shown in Figure 2. The axial velocity is normalized by exit velocity at the jet axis $U_0 = 17{,}87$ m/s. Figure 2 clearly shows characteristic regions of premixed acetylene flame: region of flame front, region of constant velocity, developing region and fully developed jet flow region.

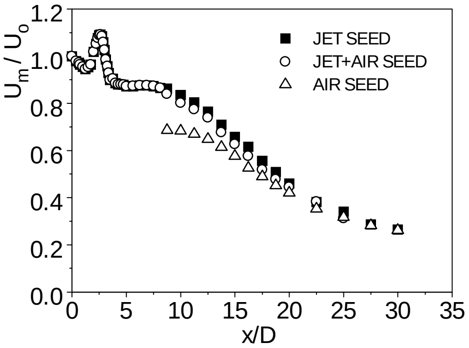

Figure 2. Mean velocity along the flame axis for conditional and unconditional seeding.

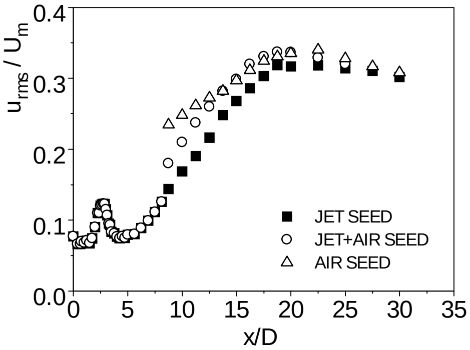

Figure 3. Turbulence intensity along the flame axis for conditional and unconditional seeding.

The region of flame front ends approximately 3 diameters downstream of the burner exit. In paper [1] it has been shown that the length of the constant velocity region depends on the mixture fuel to air ratio. This region is characterized by relatively sharp increase in axial velocity followed by axial velocity decrease. The region of constant axial velocity ends 8.5 diameters downstream of the burner exit, where fluid originating from the air penetrates to the flame centerline. This region is a result of a fluid flow relaminarization just beyond the flame front region, due to a high temperature of acetylene combustion. Calculated adiabatic temperature of the combustion for acetylene/air mixture is $T_A = 2950$ K. No measurements conditioned on the surrounding air could not been carried out for axial distances $X/D < 8{,}5$. In this region, fluid originating from the surrounding air did not penetrate to the flame axis. For axial distance $X/D < 8{,}5$ the mean axial velocity of fluid originating from the jet is considerably higher than the mean axial velocity of fluid originating from air. The resulting unconditional velocity statistics immediately downstream the constant velocity region, are close to the mean velocity of fluid originating from the jet. The difference between unconditional and conditional velocity statistics decrease further downstream. Conditional and unconditional mean velocity statistics for axial distances $X/D > 30$ agree to the extend of the measurement accuracy.

Large eddies of entrained cold air have much higher density and thus greater inertia than the eddies of combustion products. The eddies of cold gas travel in axial direction much slower, while combustion products essentially accelerate around. All eddies in the flow are continually breaking down into 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 eddies of surrounding air continue to be engulfed into flame, further reducing velocity.

Turbulence intensity distribution along the flame axis, also both for conditional and unconditional seeding, shown in Figure 3, has been normalized using the 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 velocity at the flame axis increases. After the increase of the turbulence intensity at the flame front, it considerably decreases in constant velocity region characterized by relaminarization of flow and absence mixing process between combustion products and surrounding air.

A rapid downstream increase of turbulence intensity at the flame axis corresponds to the point where the eddies of air entrained from the flame surroundings have finally reached the flame centerline, and to the start of intensive mixing process between combustion products and surrounding air. The increase of turbulence intensity also corresponds to the point where the mean axial velocity start to decrease. Obviously, large density difference delays the mixing process, with downstream increase of turbulence intensity and intensification of mixing process.

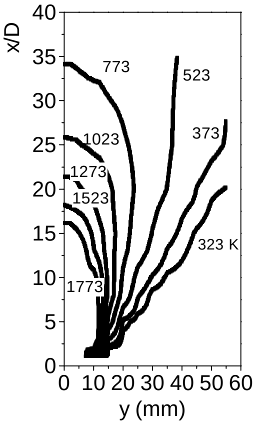

Figure 4. Isotherms in the flame.

Figure 4. show isotherms in a premixed acetylene flame. Temperature measurements with the Pt-PtRh10% thermocouple were possible in regions with temperatures below 1973K, and because of that isotherms do not show temperature values over 1773K.

Obviously from Figure. 2 is expect that in region $0 < X/D < 8{,}5$ around the flame axis there is the region of high temperature. This temperature brings a stream relaminarisation beyond the flame front and a formation of constant velocity region. Downstream of constant velocity region and with increasing the mixing processes between combustion products and surrounding air, temperature decreases and disappear region of constant velocity.

3.2. Radial profiles of the mean flow velocity, turbulence intensity and turbulent stress $\overline{uv}$

Axial mean velocity, radial mean velocity, turbulence intensity and turbulent stress $\overline{uv}$ in different cross-sections, for conditional and unconditional statistics are shown in Figure (5-7). The mean velocity and turbulent stress $\overline{uv}$ are normalized by unconditional mean velocity at the axis U_m, radial coordinate is normalized by the distance from the flame axis, b, where the unconditional axial mean velocity is half the unconditional mean axial velocity at the flame axis. The axial turbulence intensity distributions are normalized using the local mean velocity.

For axial distances $X/D = 5$ and $X/D = 8$, mean axial and radial velocities for conditional jet seeding and unconditional seeding, in central region around flame axis have constant values. In this region there is no mixing between combustion products and surrounding air. Decrease of mean axial velocity in cross-section $x/D = 5$ starts at the point where the mixing process between surrounding air and combustion products begins. As Figure 5. shows, mean axial velocity conditioned on air seed and on jet are different. At all radii the mean axial velocity conditioned on jet is larger than the mean axial velocity conditioned on air. Therefore, in general, fluid originating from the surrounding air has lower velocity than the fluid originating from combustion products. The values of unconditioned mean axial velocity near the flame axis are close to the values of mean axial velocity conditioned on jet seed. Close to the jet boundary, these values approach the value of the mean axial velocity conditioned on air seed, showing that in this region fluid originating from surrounding air dominates. Mean axial velocity profiles for axial distances $X/D = 15$ have shape characteristic for fully developed region of an isothermal jet.

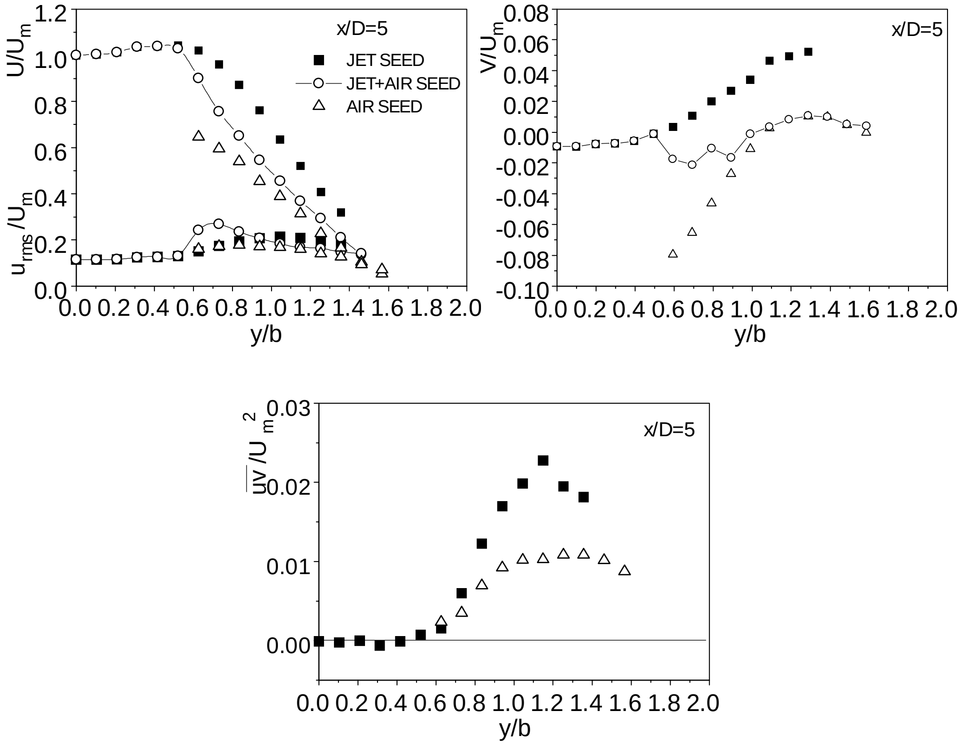

Figure 5. Profiles of mean axial, radial velocity and turbulent stress $\overline{uv}$ at axial locations $x/D = 5$.

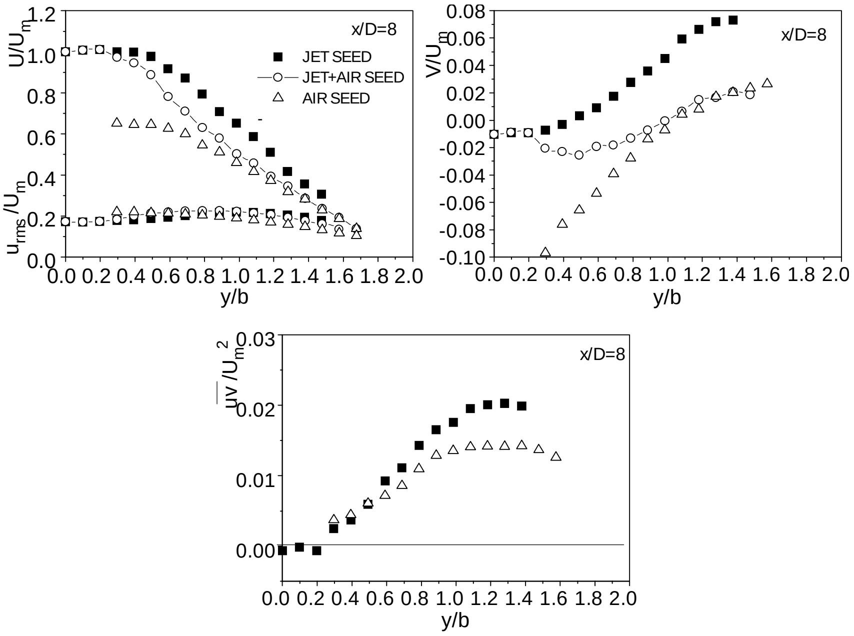

Figure 6. Profiles of mean axial, radial velocity and turbulent stress $\overline{uv}$ at axial locations $x/D = 8$.

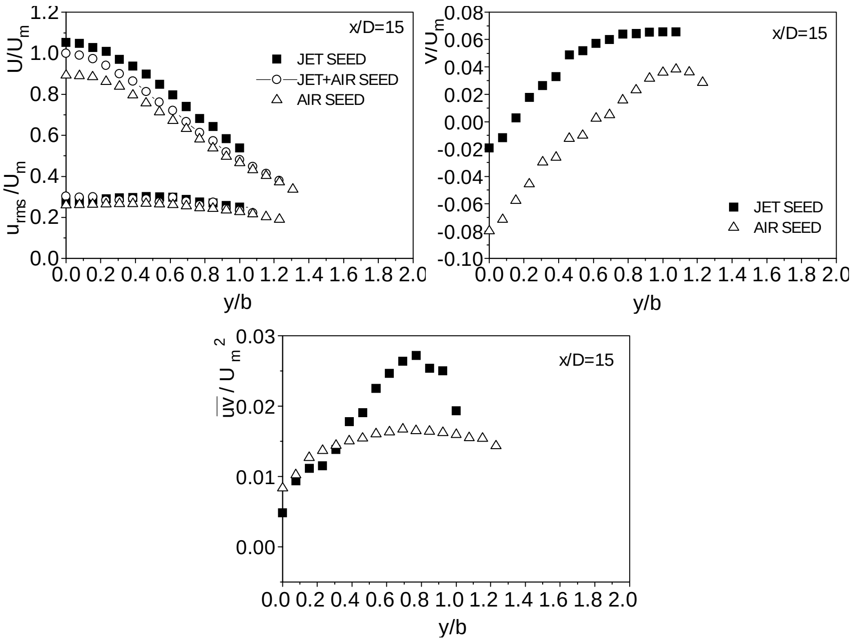

Figure 7. Profiles of mean axial, radial velocity and turbulent stress $\overline{uv}$ at axial locations $x/D = 15$.

The axial turbulence intensity distributions conditioned on jet seed and unconditioned at axial distances of $x/D = 5$ and $x/D = 8$, Figure 5 and Figure 6, are low and constant in the region where there is no mixing between surrounding air and combustion products. This indicates that the measurements were based mainly on the fluid particles originating from the jet. The turbulence intensity is increased in the region $0.5 < y/b < 1,25$, where the mixing of the jet fluid and surrounding air takes place, coinciding with the region of maximum velocity gradient.

The mean radial velocities for unconditional and conditional seeding at axial distances $x/D = 5$, $x/D = 8$ and $x/D = 15$ are shown in Figure (5-7). The radial velocity profiles indicate entrainment of surrounding air (negative values) and outward expansion of fluid originating from the jet (positive values).

Region in which a turbulent stress $\overline{uv}$ has zero value is a region where there is no turbulent mixing and change in velocity and turbulent intensity in radial and axial direction. We can see the existence of laminar flow in this region, due to the relaminarization of fluid flow. The increase of turbulent stress corresponds to a starting point of mixing In every cross section the maximum of turbulent stress obtained by the particle seeding only in the jet is higher then the maximum turbulent stress obtained by the particle seeding only in surrounding air.

3. PROBABILITY DENSITY DISTRIBUTIONS

An insight into the statistical properties of the instantaneous velocities in acetylene flame can be gained from their corresponding probability density distributions.

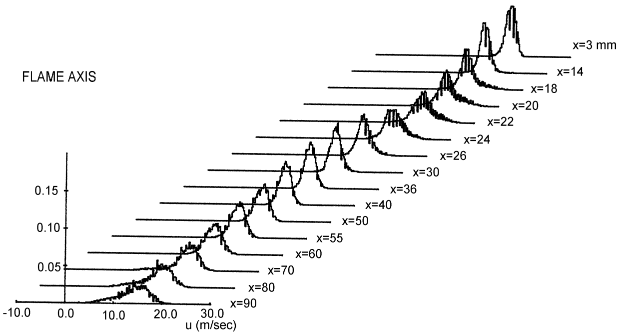

Figure 8. $Pdf'(u)$ along the flame axis

Figure 8 shows $Pdf(u)$ of the axial velocity components at the flame axis, conditioned on the jet. This figure clearly shows the increased levels of turbulence intensity at the flame front, which are reduced downstream. In the constant velocity region, velocity fluctuations are reduced and the $Pdf(u)$ become sharper. In the developing region, where turbulence fluctuations increase, a drop of the $Pdf(u)$ maximum can be see.

Figure 9 shows $Pdf(u)$ in cross-section at the axial distance $x/D = 5$, for unconditional seeding. The turbulence intensity is constant for radial distances $y = 5$ mm, where there is no mixing between surrounding air and combustion products. For distances $6 < y < 11$ all velocity $Pdf(u)$ are bimodal with two separated maximum corresponding to the combustion products and surrounding air. The bimodal shape of $Pdf(u)$ disappears closer to the flame edge, where fluid from the surrounding air dominates.

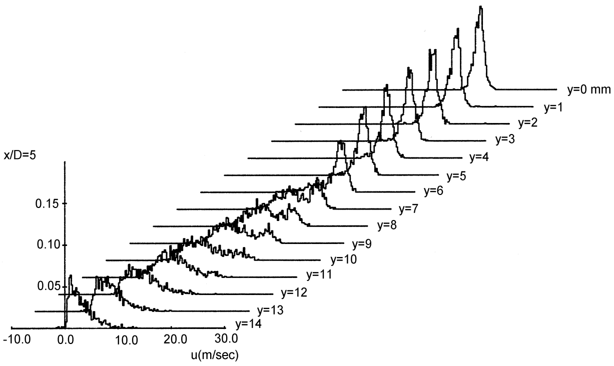

Figure 9. $Pdf(u)$ at the axial location $x/D = 5$.

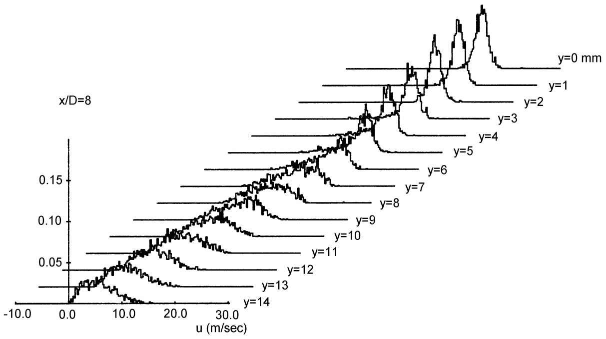

Figure 10. $Pdf(u)$ at the axial location of $X/D = 15$.

On Figure 10 distribution of probability density function of velocity $Pdf(u)$, on axial distance $x/D = 8$, is shown. Constant velocity region extends to the $y = 3$ mm distance. In this region probability density functions $Pdf(u)$ have a similar shape. This confirms the fact that in this region turbulence intensity has constant value. On the radial distances $y > 3$ mm, mixing process between combustion products and surrounding air is taking place. $Pdf(u)$ in this region have bimodal shape which disappear with approach to the jet edge.

Because of the turbulization of fluid flow and the decrease in density difference at downstream cross-sections, breakdown of the large eddies happen, and the mixing between combustion products and the surrounding air is intensified. The $Pdfs(u)$ at the axial distance of $x/D = 15$, Figure 11, cannot show bimodal shape seen at the axial distance of $x/D = 5$. The mean velocity and turbulence intensity profiles at axial distances $x/D > 15$ 8 are similar in character to those of the fully developed region of an isothermal jet.

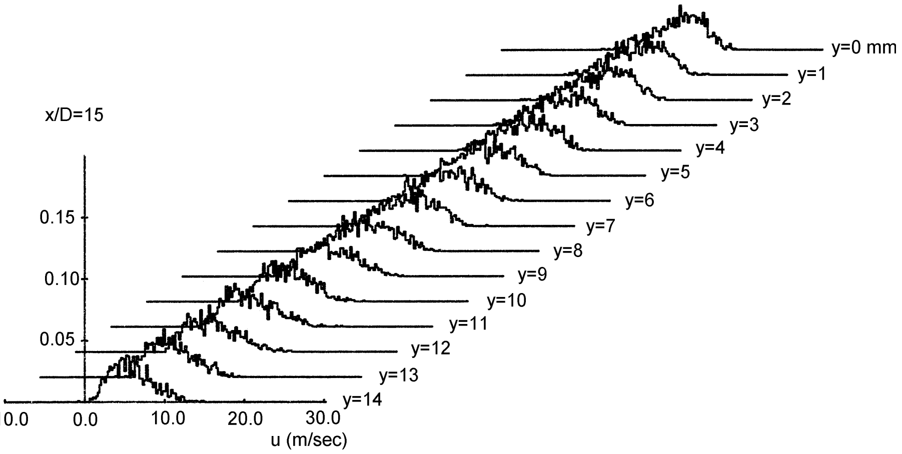

Figure 11. *Pdf*(u) at the axial location $x/D = 15$.

4. CONCLUSIONS

The results of LDA measurements for three different particle seeding points (in premixed unburnt reactants only, in surrounding air only and in both reactants and surrounding air) show that this seeding technique provides a useful marker for fluid elements originating from the combustion products and surrounding air. The resulting conditional and unconditional velocity statistics provides valuable information on details of the mixing process between these two fluids and the contribution of particular parts of the flow to the whole flow.

In the region of the flame front and constant axial mean velocity, large differences between both axial and radial velocity components of cold eddies of surrounding air and hot eddies of combustion products have been detected. Due to the high viscosity in this region the turbulence intensity is very low. This also confirm that large density difference delays and suppress the mixing process in this region. In this region of the flame the area where mixing process takes place is very narrow.

These flow characteristics indicate that downstream the flame front a sort of "potential core" is formed, characterized by constant mean velocity, low turbulence intensity and weak mixing in the narrow region on the boundary with surrounding air.

Downstream from this apparent "potential core", with diminishing density difference, intensive mixing takes place, with sharp increase of the turbulence intensity.

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STRUJNO POLJE TURBULENTNOG ACETILENSKOG PLAMENA

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U ovom radu su dati profili prosečnih komponenti aksijalnih i radijalnih komponenti brzina, intenzitet turbulencije, Rejnoldsov napon $\overline{uv}$*, funkcije gustine verovatnoće brzine i prosečnog temperaturskog polja u različitim poprečnim presecima prethodno stvorene mešavine acetilena i vazduha sa stehiometrijskim odnosom. Merenja brzinskog polja su obavljena jedno-komponentnom laser-Dopler anemometrijom, dok se za merenje temperaturskog polja koriste termoparovi Pt-PtRh10%. Zasnovan na merenjima brzinskog polja, za tri različite tačke zasejanja analizirani su 1) u smeši nesagorelih reaktanata samo, 2) u okolnom vazduhu samo, i 3) kako reaktanata tako i okolnog vazduha i produkta sagorevanja u karakterističnim oblastima acetilenskog plamena.*