CHARACTERISTICS OF PRECESSING VORTEX CORE IN THE LPP COMBUSTOR MODEL

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ABSTRACT

This work is devoted to the study of swirling flow in a model LPP combustor with the purpose of choosing optimal boundary conditions that may lead to low NOx emission at high fuel efficiencies. In this context, experiments, conducted on a LPP chamber, under non-reacting and reacting conditions, have revealed the presence of a swirl jet breakdown zone and a flow pulsation caused by hydrodynamical instability in form of PVC. Parameters of vortex flow with the PVC, such as precession frequency and swirl level defined through measured radial pressure gradient, were used to characterize flow regime and to choose optimal combustor configuration.

Good performance of LPP combustor corresponds to swirling flow regime with the developed and stable recirculation zone defined according to characteristic maps for frequency and pressure drop measurements at isothermal conditions.

INTRODUCTION

Swirling motion is widely used in many technological installations (Gupta et al., 1984; Heitor and Moreira, 1992; Alekseenko and Okulov, 1996; Gupta et al., 1998; Anacleto and Heitor, 2000). In burner devices the organization of intensive vortex flow promotes flame stability and intensification of heat and mass transfer processes. The recent work by Anacleto and Heitor (2000) for LPP (Lean Premixed Prevaporized) combustor model pointed that an intensive swirling flow allows improving mixing processes in premixing chamber that in turn ensures very low NOx emission at high fuel efficiencies. Flow swirling provides also flame stabilization in combustion section of LPP by means of central recirculation zone formed due to breakdown of intensively swirled jet. The reverse flow playing basic role in flame holding is associated with flow pulsation in form of Precessing Vortex Core (PVC, Gupta et al. – 1984; Yazdabady et al., 1994) producing by a shear layer on a boundary separating upward and downward flows. Strong flow instability in form of rotating intensive concentrated vortex produces pulsation of velocity and pressure which cause nondesirable factors such as loud noise and vibrations which in turn may be amplified at coupling with the natural acoustics modes of a combustor.

Impact of combustion on PVC depends on several factors such as way of fuel supply and mixture ratio (Syred and Beer, 1973; Bertrand and Michelfelder, 1976; Coats, 1996). PVC can be suppressed in turbulent diffusion rich flames but in lean premixed flames large amplitude pulsations in form of PVC are detected.

This work is devoted to the study of PVC characteristics in LPP laboratory combustor with final aim to develop methods (active and passive) for amplification of positive factors of PVC and reduce destructive ones. The experiments should provide information on impact of the precessing structure on the process of flame stabilization at very lean conditions producing low level of NOx emission. It's s upposed that the results of PVC characteristics study will allow to identify values for external excitation of rotating vortex and thus to control combustion process (Gursul, 1996; Paschereit et al., 1999).

The main purpose of the current experiments phase is to choose optimal boundary conditions providing effective LPP combustor operation with the low pollutants emission. This means that since basic role in flame stabilization plays existence of central recirculation zone, we should find a regime with the developed and stable recirculation flow where we can reliably stabilize flame. The work stages:

- isothermal conditions - free swirling jet;
- isothermal flow – swirling jet in cylindrical chamber;
- checking optimal flow regime in combusting conditions.

Integral parameters such as average PVC frequency and total radial pressure gradient in vortex were used for the characterization of swirling flow regime.

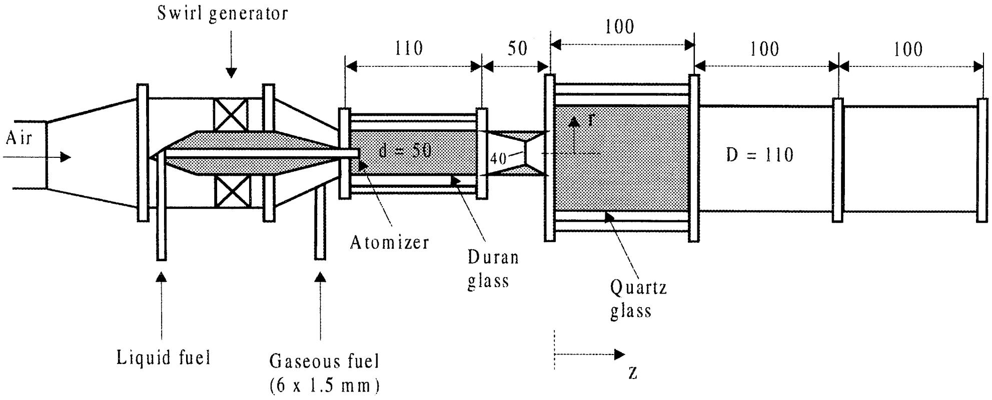

Figure 1 : Diagram of the experimental rig.

EXPERIMENTAL TECHNIQUE

In Fig.1 the sketch of the experimental rig, similar to that used by Anacleto and Heitor (2000), is presented. It consists of blade swirler, premixing duct with inner diameter d = 50 mm (ending by an inset with a diameter 40 mm) and combustor chamber with diameter of D = 110 mm and length up to 300 mm. Gaseous (propane) and liquid fuels (kerosene) injected as it shown in the Fig. 1 were used at combustion conditions. Experimental system included preheater changing air temperature up to $T_{air} = 500°\mathrm{C}$. For reacting flows additional parameter equivalent ratio Φ was applied. Combustion studies in the present work were done at lean conditions corresponding $\Phi = 0.5$. Basic regime parameters were Reynolds number $\boldsymbol{Re = U_0\, d\, /\, \nu}$ (U_0 - average axial velocity in the premixing duct based on flow rate) and swirl parameter S (defined through swirler geometry, Gupta et al., 1984), which could be varied by changing air flow rate Q and blades angle accordingly.

For characterizing vortex flow regime integral parameters were measured: averaged frequency of PVC rotation, total radial gradient of static pressure across vortex ΔP (differential pressure between vortex axis taken from atomizer hole and pressure on premixing chamber wall taken before converging-diverging inset) measured when jet fuel is not used.

Pressure drop across vortex or total radial gradient of static pressure is important parameter of vortex flow since defined by distribution of tangential velocity component and thus indicates intensity of vortex (Alekseenko et al., 1999). It can be demonstrated with using Euler equations, which give in axisymmetrical case with dominant rotational motion ($w(r)$ – tangential velocity):

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{w^2}{r}. \qquad (1)$$

By integrating both parts from $r = 0$ till $r = R$ (chamber wall) we obtain

$$\Delta P = P_R - P_0 = \int_0^R \rho\, \frac{w^2}{r} dr, \qquad (2)$$

where P_0 is the pressure at vortex axis and P_R - pressure at chamber wall. It can be noticed that total radial pressure gradient can be related with the integral value of tangential velocity and consequently swirl degree of flow.

Parameters of premixing chamber, namely, diameter and averaged velocity were used to calculate dimensionless characteristics: Strouhal number $\boldsymbol{Sh = f\, d\, /\, U_0}$ and differential pressure $\boldsymbol{\Delta P^* = 2\, \Delta P\, /\, \rho\, U_0^2}$.

Quantitative flow visualization was performed using of high-speed CCD camera (Kodak Motion Corder Analyzer). Standard aluminum particles and oil smoke were used as flow markers which were made visible with using powerful laser and cylindrical lens beam expander forming light sheet with thickness 2 *mm*.

For detail measurement of flow field and flame characteristics TSI's Laser Doppler Velocimeter, fine platinum-13% rhodium-platinum thermocouples

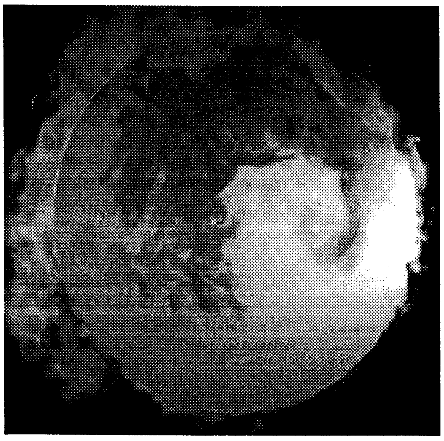

Figure 2 : Image of flow pattern with the PVC (seen on right side of the picture) rotating in clockwise direction. Visualization by smoke, S = 1.26, Re = $6.9 \cdot 10^3$.

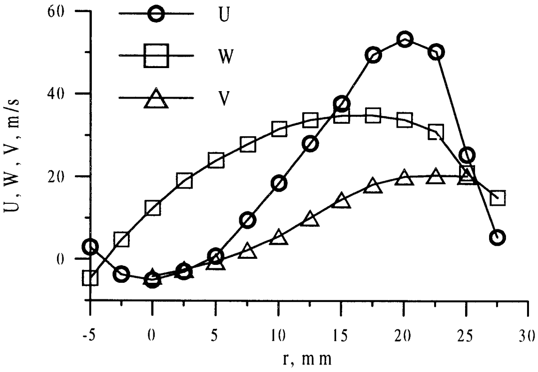

Figure 3 : Velocity boundary conditions – profiles of averaged axial U, tangential W and radial V velocity components at exit of the premixing chamber. Heated air with T_{air} = 300°C, S = 1.05.

and standard species analyzer system were used (Anacleto and Heitor, 2000).

For registration of pressure oscillations produced by PVC, a semi-infinite probe system (Fernandes and Heitor, 1999) based on condenser microphone B&K-4165, with tip installed outside swirling jet (at z = 10 mm, r = 30 mm) was used. Signal from microphone was acquired by Fulcrum DT3808 board installed into a PC and processed to obtain dominant frequency. The parameters of data acquisition and averaging processing procedure provided uncertainty in PVC frequency measurement of ± 1.22 Hz.

RESULTS AND DISCUSSION

Free swirling jet

First stage of experiments was performed with air at isothermal condition without combustion chamber (all three sections with the diameters 110 mm were removed, see Fig. 1). It was aimed to explore initial flow conditions defined by swirling system and premixing duct geometry. Further studies should clear up influence of confinement and combustion on swirling jet and PVC characteristics.

Flow visualization. To understand main features of flow structure of swirling jet visual studies were performed. In Fig. 2 a video frame of smoke visualization of PVC in vertical cross section is shown. Sickle-like dark region inside jet corresponds to area of reverse flow (as it was revealed at analyzing video record of flow pattern in horizontal cross section) containing ambient air almost without smoke. The vortex core is attached to one of the tips of sickle and moves before it.

As we could see instantaneous flow structure with PVC is more complicated than it is usually presented in time averaged velocity profiles. Complex spatial character of flow field in presence of PVC was demonstrated by Yazdabadi et al. (1994) with using phase-averaged measurements in cross section of cyclone separator exit. Our qualitative results coincide with the mentioned measurements indicating the effect of attaching reverse zone to the PVC center. Their results also indicate the effect of lagging reverse flow similar to that we observed. As the authors explain, swirling motion produces low pressure at the vortex center according to the Eq. 1, which in turn is transferred after vortex breakdown in axial pressure gradient driving recirculation flow directed to the stagnation point at a vortex axis. Since, stagnation point, in case of spiral type of breakdown, is displaced from the chamber axis and rotates around it (Brücker, 1993; Billant et al., 1998), the recirculation flow area should rotate either. Measurements of Yazdabady et al. (1994) show an effect, which could not be visualized in our experiments, namely, sticking zone of maximal forward velocity zone to the rotating vortex center.

No doubt that these details of flow structure are very important for analyzing swirl combustion processes. To understand how flame propagates inside precessing vortex structure and how characteristics of this structure influence on flame stabilization, phase resolved measurements of temperature and velocity field (Yazdabady et al., 1994, Fernandes and Heitor, 1999), planned to be done in future, are necessary.

Velocity boundary conditions. Fig. 3 presents averaged velocity profile in cross section near the premixing chamber exit with hot air (T = 300°C) so these profiles should be also boundary conditions for LPP operation mode with combustion of liquid fuel when air preheating is applied. The profiles indicate usual features of flow after breakdown of intensively swirling jet: intensive axial and rotational cone flow filled with weakly rotating zone of reverse motion. According to radial and tangential velocity values at r = 20 mm (maximum of axial velocity) the cone

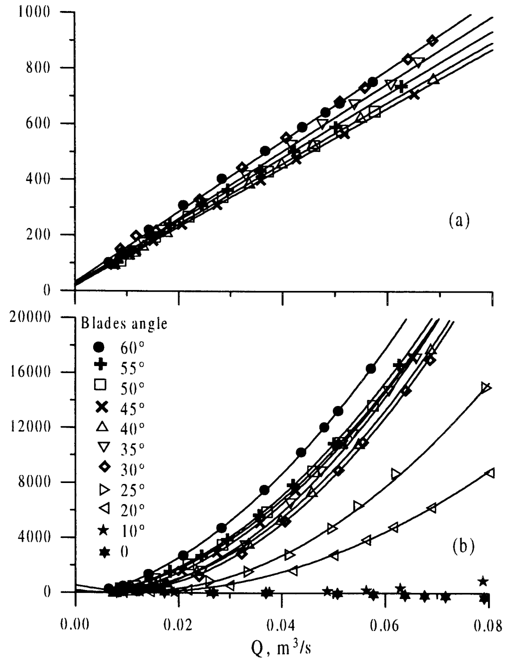

Figure 4 : Dominant frequencies in spectra of acoustic probe signals for a free swirling jet (a) and total radial pressure gradient across vortex in the premixing duct (b), $T_{air} = 25°C$.

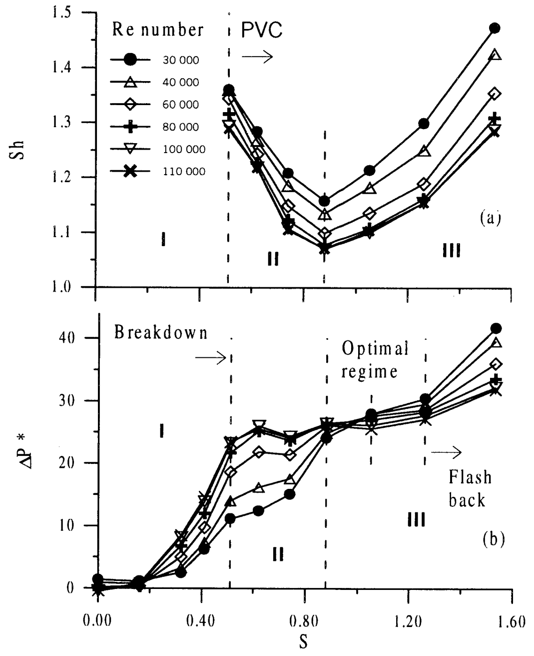

Figure 5 : Dimensionless frequency (a) and total radial pressure gradient across vortex (b) vs. swirl number.

angle is equal to value of about 42° that is seemed less than for reacting conditions (approximate jet cone angle measured on photo Fig. 6 d should be around 65-70°). This coincides with the known effect of combustion when recirculation zone becomes more shorter, stronger and radially wider (Brum and Samuelsen, 1987).

Acoustic measurements. Figure 4 shows results for non-reacting conditions: dependences of PVC rotation frequency and total radial pressure gradient ΔP on air flow rate and blades angles of swirler. Forms of dependences have expected features – linear for frequencies and quadratic for pressure gradients. These characteristics in dimensionless form indicate expressed stages of vortex core and swirl jet developing at swirl degree increasing (Fig. 5). In region I circulation of core growths sharply that corresponds to sharp increasing of radial gradient of pressure. The jump like vortex intensification is limited by vortex breakdown and arising central recirculation zone and as consequence forming PVC on which appearing discrete peak in pressure and velocities signals spectra pointed. Further increase of swirl number is compensated by recirculation zone spreading and expansion of vortex core and as results we have region II with constant radial pressure gradient (for large *Re*). Precession frequency in this region decreases up to minimal value due to growth of PVC rotation radius. After full developing recirculation zone PVC rotation frequency starts to increase in region III as it was usually noted in previous studies (Chanaud, 1965; Cassidy and Falvey, 1970). As it could be seen from Fig. 5 b the vortex flow is developing evidently in transitional region II at *Re* number increasing either. Flow becomes fully developed (independent from *Re*) at rather high *Re* numbers more than $8 \cdot 10^4$. This fact coincides with the data of Cassidy and Falvey (1970) obtained for air flow (for water flow swirled by blade swirler this boundary *Re* number is more less and of about 10^3 as it was reported by Chanaud, 1965) but way of approaching dependences to constant level is opposite. In our case the dimensionless frequency decreases at growing flow rate. The same effect we can see for differential pressure in region III but in region I and II vortex intensity is growing at increasing *Re* number. The complex behavior of the flow characteristics is connected apparently with the development of swirling recirculating flow possessing free stagnation point. Changing regime parameters leads to spreading recirculation zone (increasing cone angle) and also to upstream shifting stagnation point as it takes place during vortex breakdown in vortex tubes for example (Escudier, 1988).

It's evident that we should avoid operation of combustor in transitional region and choose regime with developed recirculation zone and steady flow regime when we can reliably stabilize combustion. According to characteristics maps (Fig. 5) it was supposed to obtain the good device performance in region III at S > 0.88 where flow exhibits stable parameters at varying both flow rate and swirl number. Actually, at experiments with the combustion optimal combustor characteristics, based on temperature and chemical species field, were found at S = 1.05, e.g. inside the region indicated above (Fig. 5). Further increasing swirl intensity when we move in region III leads to flashback of flame into premixing chamber. This effect is undesirable for LPP combustor work because reaction takes place in presence of not complete mixing and vaporizing fuel. Flash back effect represents sudden burst of vortex core increasing its size. We can say that at $S > 1.26$ vortex in premixing chamber exist at supercritical condition (Benjamin, 1962) when small changing parameters can lead to large variations in flow structure.

Thus, we are restricted in varying regime conditions and further extending flammability limits should be succeeded by modification (with a proper changing near nozzle exit geometry, external acoustical exciting, etc.) of flow structure in breakdown zone that in turn requires, as it was mentioned, detail study of instantaneous flow pattern with the processing vortex core.

Reacting flow in combustion chamber

Results obtained for swirl flow in combustion chamber at burning gaseous fuel at the same conditions as for isothermal air flow indicated that for large level of swirling, frequencies of PVC are just slightly amplified in comparison with the isothermal flow. Weak influence of combustion on other vortex flow characteristics as radial pressure gradient is detected as well. Dominant frequency for reacting flow corresponds to PVC with the amplitude of pulsation about the same value as for nonreacting flow.

The results of model experiments with the cold air and gaseous fuel combustion supported next step of studies of more complex experimental system with combustion of liquid fuel where processes of fuel vaporizing in the premixing duct play also essential role for achieving low pollutants emission. As it was revealed by the temperature and species concentrations fields measurements the level of flow swirling, defined as optimal in sense of stable swirling jet aerodynamics, provided complete fuel vaporizing before combustion zone, which ensured local lean conditions in combustion chamber and consequently low NOx emission.

Fig. 6 shows axial development of PVC characteristics for free isothermal swirling jet and some sample results obtained for reacting swirled flow with the combustion of liquid fuel at geometrical conditions pointed in Fig. 5 as optimal. We can notice full correspondence of these results. Maximal radial swirl jet spreading coincides with the maximal central backward velocity and corresponds to point of PVC breakdown. Abrupt disintegration of coherent PVC structure is caused by development of central counter current flow and consequently intensive mixing processes that promotes the flame stabilization in the beginning of combustion chamber and high fuel efficiency of combustor.

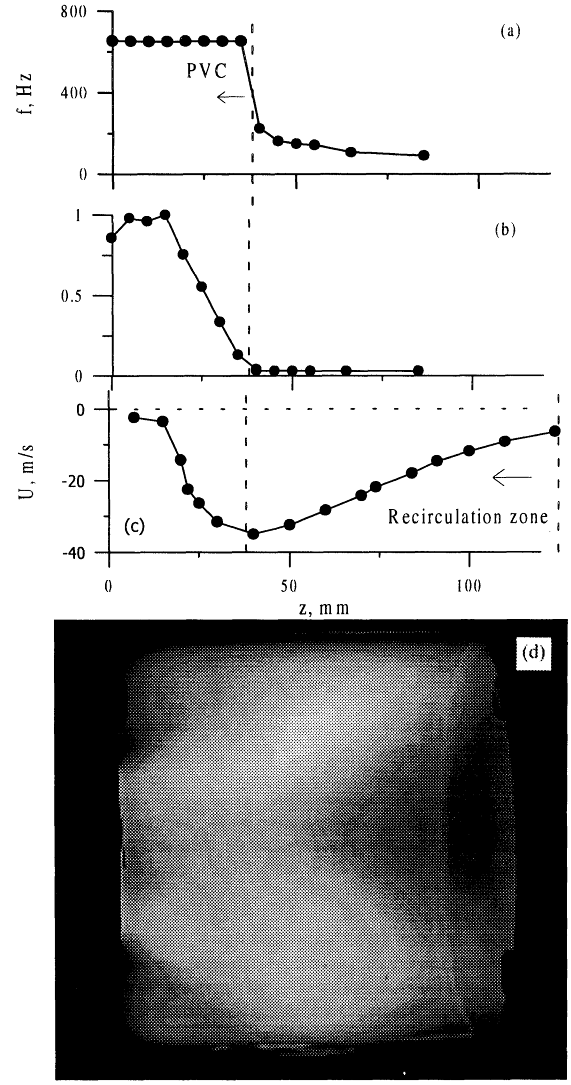

Figure 6 : Axial development of PVC structure (frequency and amplitude of dominant harmonic, normalized by its maximal value, (a) and (b) consequently) in isothermal free jet with volumetric air flow rate $Q = 0.054$ m^3/s, $T_{air} = 20°C$ and S = 1.26, and centerline axial velocity (c) as well as flame picture (d) in combustion chamber with combusting conditions (jet fuel, $\Phi = 0.5$, mass air flow rate was 0.046 kg/s with $T_{air} = 300°C$, S = 1.05).

CONCLUSIONS

Experimental study of flow characteristics in LPP combustor model with applying various measurements techniques has been performed.

Preliminary results obtained from visualization and acoustic measurements for isothermal swirling air flow and lean swirl stabilized flame show the presence of intensive flow pulsation caused by hydrodynamical instability in form of PVC. Integral parameters of flow such as frequency of PVC rotation and total radial pressure gradient in premixing chamber were used to characterize flow regime. Dependencies of these parameters vs. flow rate and swirl number brought to light new results on vortex flow development after swirl jet breakdown, consisting in decreasing PVC frequency at *Re* and swirl numbers increasing, that is connected in turn with the features of recirculating flow development in swirling jet possessing free stagnation point.

New result consists in fact that flow parameters, in the presence of PVC, don't depend on boundary conditions downstream of premixing chamber. Characteristics of PVC such, as precession frequency and core circulation, are defined by vortex flow formation in premixing chamber in isothermal conditions. So that all the parameters measured were found the same for free isothermal swirling jet, swirling confined isothermal flow and reacting flow at lean conditions.

Good performance of LPP combustor corresponds to swirling flow regime with developed and stable recirculation zone defined according to characteristic maps for frequency and pressure drop measurements at isothermal conditions.

Further experiments will include multipoints acoustic measurements to define spatial characteristics of PVC namely angular and axial wavenumbers and phase averaged LDV and temperature measurements to obtain instantaneous spatial flow and temperature fields (Yazdabady et al., 1994, Fernandes and Heitor, 1999). This information will be used for developing methods of coherent structure exciting to control combustion characteristics with the purpose of providing flame stabilization at ultra lean conditions.

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