ABSTRACT

For lean premixed combustion the NO<sub>x</sub> emission can be reduced by optimizing the degree of fuel-air mixedness. Since both temporal and spatial mixture variations are of importance, the time resolved planar laser technique of acetone tracer-LIF (laser-induced fluorescence) is used to characterize the mixing quality in an one-to-one scale segment of a Siemens ring shaped gas turbine combustor. Variations of the combustor geometry and of additional mixing devices have been tested, showing the potential to increase the mixing quality. Subsequent tests in a fired atmospheric test rig confirm the influence of the mixing quality, leading to up to 30 % further reduction of the NO<sub>x</sub> emissions.

INTRODUCTION

Lean premixed combustion has the potential to reduce the NO<sub>x</sub> formation significantly compared to non-premixed combustion, since especially the flame temperature is reduced, leading to less thermal NO<sub>x</sub> formation. Thus lean premixed combustion is seeing increased application in gas turbines as an alternative to non-premixed combustion. In lean premix combustors a significant portion of the combustion air is mixed with fuel upstream of the primary reaction zone. Ideally, this produces a homogeneous lean fuel-air mixture. In practice, however, the mixing zone between fuel and air has to be as small as possible in order to minimize the potential of hazardous damage in the case of a flash-back of the flame. Thus, in real gas turbines the mixing quality often might be quite imperfect.

The formation of nitrogen oxides (NO<sub>x</sub>) depends on different reaction paths. For lean premixed combustion of natural gas the thermal mechanism, prompt mechanism, and the reaction via the N<sub>2</sub>O path are of importance (see e.g. Steele et al. 1995, Warnatz 1996). Without discussing details of the reaction process here, experimental data and numerical analysis show a nonlinear decrease of the NO<sub>x</sub> emission for increasing air-fuel ratio for lean mixtures (Warnatz 1996 and others), as is shown in the qualitative sketch in Fig. 1. Following from this nonlinear behavior, the NO<sub>x</sub> emission depends not only on the mean air-fuel ratio but also on the fluctuation of this ratio (or in other terms of the degree of unmixing). In Fig. 1 this effect is visualized in a simplified way for two different degrees of local unmixing. Note that locally leaner and richer mixture pockets do not balance the average NO<sub>x</sub> production rate, as long as the NO<sub>x</sub> emission is a nonlinear function of the air-fuel ratio (Fig. 2). Calculations including detailed kinetics have shown this influence of the mixture homogeneity on NO<sub>x</sub> emission in a quantitative way (Fric 1993, Prade et al. 1996, Barnes and Mellor 1997). Thus, in order to reduce the NO<sub>x</sub> emission as far as possible, not only the mean stoichiometry but also the fluctuation of the local stoichiometry should be taken into account.

Additionally, as can be seen from Fig. 1, strong fluctuations of the local air-fuel ratio might lead to conditions with local mixtures beyond the lean extinction limit which might result in increased emissions of unburnt hydrocarbon and probably in flame instabilities. Thus, in order to prevent these effects, it might be necessary, to operate a burner with high fluctuations with a lower mean air-fuel ratio, resulting in additional NO<sub>x</sub> emission. Both effects together show that fuel and air should be mixed with high quality. Thus, in order to come closer to the goal of "single-digit-NO<sub>x</sub>" conditions (NO<sub>x</sub> concentration below 10 ppm), the optimization...
of the mixing quality within the limited space of gas turbine burners seems to be an important step.

For the influence of the unmixedness, not only spatial inhomogeneities but also temporal fluctuations are of importance, as is visualized in Fig. 2. Thus, for an experimental characterization of the mixture fluctuations, it is not sufficient to measure the temporal average of the air-fuel ratio at separate positions. Instead, spatially and temporally resolved measurements are necessary.

The extent of mixing is often quantified by the unmixedness $U$ (Danckwerts 1952),

$$U = \frac{c'_{\text{rms}}^2}{\bar{c} \cdot (1 - \bar{c})} = \left(\frac{c'_{\text{rms}}}{\bar{c}}\right)^2 \cdot \frac{\bar{c}}{1 - \bar{c}}$$  \hspace{1cm} (1)

where $\bar{c}$ is the mean fuel concentration and $c'_{\text{rms}}$ is the rms fluctuation of the fuel concentration. From the experimental point of view, the normalized rms fluctuation

$$R = \frac{c'_{\text{rms}}}{\bar{c}}$$  \hspace{1cm} (2)

is easier to determine from planar measurements than the rms fluctuation by itself, and will be used in this work.

In the following, the utilization of a modern planar laser diagnostic method is described for the characterization of the temporal and spatial fuel-air mixing quality. With this tool, different mixing devices with varied geometrical arrangements have been tested on an one-to-one scale segment of a Siemens ring shaped gas turbine combustor.

**EXPERIMENTAL SETUP**

A segment of the Siemens V64.3A ring shaped gas turbine combustor was rebuilt in its original size, using fiber glass laminate and acrylic glass. Five Siemens HR hybrid burners (Prade et al. 1996) were installed in the segment, so that the central burner could be investigated without the disturbing influence of the side walls. The mixing experiments were conducted as atmospheric cold flow investigation (25°C), and the original fuel (natural gas) was replaced by nitrogen for safety reasons.

The mean flow velocity was chosen to correspond to that of a typical operating point of the high-pressure combustor, while for the ratio between fuel and air flow, momentum scaling was applied.¹

In order to visualize the mixing of fuel and air, the fuel stream was seeded with acetone vapor, which was detected by planar laser-induced fluorescence (PLIF). The use of acetone as a tracer is well established in gaseous non-reacting and reacting flows (Lozano et al. 1992, Tait et al. 1993, Krämer et al. 1995, Shih et al. 1996) and, in comparison to other approaches (e.g. Mongia et al. 1996), allows a non-intrusive two-dimensional investigation of the mixture fluctuations. Nevertheless, to our knowledge, the application of acetone tracer LIF has not been reported to full scale investigations of gas turbine combustors.

Excitation of acetone was achieved by a pulsed KrF excimer laser in the ultra violet region (Lambda Physics, wavelength $\lambda = 248$ nm, 170 mJ/pulse). The laser beam was guided into

¹ The Reynolds number depends on both pressure and temperature, increasing with increasing pressure and decreasing with increasing temperature. Since both effects have opposite influence, the Reynolds number of the atmospheric cold flow experiments is only about four times lower than in gas turbine conditions.
the combustion chamber through several quartz windows (Fig. 4) and was formed to a thin light sheet of about 40 mm height and 0.3 mm width, using suitable cylindrical lenses. This light sheet defines the measurement volume, and allows essentially two-dimensional measurements in the plane of the light sheet. During the extremely short laser pulse duration of 20 ns, fluorescence of the acetone molecules is induced from the laser light. The resulting fluorescence signal is detected by an intensified CCD camera (8-bit ICCD, 640 x 480 pixel), arranged perpendicular to the light sheet and equipped with a suitable objective (Nikon f= 50 mm, spatial resolution 0.31 mm/pixel). The fluorescence signal of acetone is spectrally shifted to the visible range (broad band signal between 350 to 600 nm). This allows suppression of interfering reflections in the UV range by a standard glass lens system and an additional UV filter, blocking all signals below 390 nm (Kraus et al. 1995).

The fluorescence signal is proportional to the local number density of the acetone molecules and is therefore a measure of the concentration of the fuel flow. Acetone was vaporized in a steam driven evaporator, and was mixed with the fuel in an arrangement of three static mixers and additionally by flowing through about 10 m flexible tube of 3/4" diameter. Therefore an extremely homogeneous mixing quality between fuel flow and tracer can be assumed.

In order to quantify the signals from the acetone PLIF measurements, several possible errors have to be taken into account. Some of these errors can be eliminated by normalizing the measured rms fluctuation $\varepsilon_{rms}$ with the measured mean $\varepsilon$. The shot-to-shot variation of the laser intensity is determined to be in the range of 2%. This fluctuation is constant for all measurements and is small compared to the measured rms fluctuation. More important is the amount of noise, coming from the intensifier and camera system. If one assumes that the relative fluctuation of the fuel-air mixture $R$, the relative noise level from the detection system $N$, and the mentioned shot-to-shot fluctuations of the laser $L$ are statistically independent, the resulting measured relative fluctuation $M$ is

$$M^2 = R^2 + N^2 + L^2$$

Fig. 5: Details of the burner, and laser light sheet arrangement (schematic).
The relative noise level of the detection system $N$ can be determined from test images with uniform illumination (flat-field images). $L$ is also known, thus the relative fuel-air mixture fluctuation $R$ can be determined from Eq. 3.

Spatial variations of the laser intensity are either constant in time or have also temporal fluctuations. By determining the relative rms fluctuation $R = \frac{c_{\text{rms}}}{\bar{E}}$, the constant part of the spatial variation is normalized and has no significant influence. Temporal fluctuations of the spatial intensity variations are important at the wings of the light sheet. The resulting structures have the form of stripes which are oriented parallel to the direction of the laser beam. Therefore they can be detected easily and have to be covered out. A drift of the average laser intensity in time again is eliminated by normalizing the fluctuation intensity. The same is valid for a possible drift of the acetone flow rate.

Hence, the normalized rms fluctuation $R = \frac{c_{\text{rms}}}{\bar{E}}$ (respectively the normalized standard deviation) is determined as the primary measure of unmixedness in this work. The quantification of the corrected mean concentration field $\bar{E}$ would need additional calibration measurements which especially for the applied measurements in the full-scale combustor rig would not be easy. Additionally, flame ionization detection (FID) measurements of the mean fuel-air distribution have been done in earlier measurements, therefore no effort has been made to fully calibrate the mean concentration measurements from the tracer LIF technique.

For the premixed operation mode of the HR burner, the fuel flow is added to the air stream through several inlet holes in the blades of the diagonal swirler (Prade et al. 1996). In order to allow measurements of the mixing quality within the flow channel of the diagonal swirler, the premix channel was elongated by about 20 mm, so that the cross section of the laser light sheet could be adjusted with a distance of only 3 mm to the end of the elongation (Fig. 5). Omitting the elongation and adjusting the light sheet with the same distance to the wall did not allow measurements, because of intense background reflections. In the experiments described, pure air enters the burner through the inner channel (axial swirler). Since only the fuel stream was seeded with acetone, this part of the burner was dark in the measurements.

RESULTS

As mentioned before, the mean fuel-air distribution has been measured at the end of the premix channel with flame ionization detection (FID) in a separate investigation. Radial and circumferential profiles showed no significant inhomogeneities of the mean fuel-air distribution. While FID measurements can provide the mean fuel-air distribution, the temporal fluctuations cannot be resolved here. For that, the tracer LIF technique is used, "freezing" the flow and the mixing process with the exposure time of 20 ns.

The 'standard' configuration of the burner and four different configurations, each of them having an influence on the mixing behavior, were investigated. Two configurations (the 'mixer' and the 'perforated plate', Fig. 6) generate additional turbulence upstream of the diagonal swirler.

---

2 SIEMENS AG, internal report.
Fig. 7: Series of single-shots of the fuel-air mixing field (in false color representation) at the end of the premix channel. Shown is the left part of the premix channel. 
(a) 'standard' configuration, (b) 'mixer' configuration, (c) outer fuel inlet holes closed.

With two other configurations, the ratio of momentum between fuel and air flow has been modified, either by a reduction of the diameter of the fuel inlet holes, or by closing the outer fuel holes, while the mass flow of air and fuel were kept constant. Table 1 summarizes the investigated configurations.

| Table 1: Investigated burner configurations |
|---|---|
| 1 | 'Standard' |
| 2 | Outer fuel inlet holes closed |
| 3 | Reduced fuel inlet hole diameter (80 %) |
| 4 | 'Mixer' |
| 5 | 'Perforated plate' |

Figure 7 shows a series of single-shot measurements, comparing three of the different configurations as examples. The detected area covers the 'left' part (seen against the flow direction) of the premix channel. The images show clearly that less shot-to-shot fluctuations appear when the 'mixer' is inserted upstream of the diagonal swirler (Fig. 7b), while closing the outer fuel holes leads to an increased level of fluctuations in some parts of the detected area (Fig. 7c).

In order to quantify the mixture fluctuation, the standard deviation of 300 single-shot images relative to the average value was determined as a measure for the normalized fluctuation intensity, where the statistical analysis has been done on a pixel to pixel base. Figure 8 shows comparisons between different burner configurations. The vertical stripes are caused by shadows, coming from limited optical access of the laser input windows. In these regions no information is available.
Fig. 8: Normalized standard deviation as a measure for the fluctuation intensity. (a): 'standard configuration', (b): test of reproducibility with 'standard configuration' several weeks later, (c): configuration 2, (d): configuration 3, (e): 'mixer', (f): perforated plate.
Figures 8a and 8b have been obtained with the 'standard' configuration of the burner at two different measurement campaigns. Several weeks were standing between these two measurements, and the setup was completely removed and rebuilt in the interim. The similarity between both figures demonstrates the reproducibility of the results.

The 'standard' configuration obviously does not produce the most homogeneous mixture. The inner part of the premix channel is better mixed than the outer part while the overall level of the fluctuations is comparatively high. The maximum of the fluctuations at the left side of the channel indicate that a circumferential asymmetry of the air flow and/or the fuel flow exists. It should be noticed that the FID measurements mentioned before have not shown this effect. Obviously, the mean fuel-air ratio is homogeneous while the mixture fluctuation is not.

The figures 8c-f show results for the other configurations. The conclusion drawn from the single-shots that configuration 2 partly leads to elevated mixture fluctuations (Fig. 7c) is confirmed for some regions in the outer part of the premix channel (Fig. 8c). This is not very surprising, since the locally lean air in the outer part of the diagonal swirler, coming from the closed fuel inlet holes, induces additional inhomogeneities. On the other hand, the fuel rich inner part of the channel shows a significantly better mixing behavior than before. Since the momentum ratio between fuel and air flow is increased in this inner part, this measurement shows that a modification of the momentum ratio of the standard configuration might improve the mixing process.

Indeed, a 20 % reduction of the diameter of the fuel inlet holes, enhancing the momentum of the fuel flow, leads to a significantly homogenized mixture (Fig. 8d). Even the high fluctuations at the left side of the premix channel are compensated to a large extent (The holes in Fig. 8d are locations with high stray-light levels in this experiment).

An even better mixing quality can be achieved with the 'mixer' configuration (Fig. 8e), where additional turbulence is generated upstream of the fuel inlet holes in order to intensify the mixing process (Fig. 6a).

In contrast to the 'mixer' configuration, a 'perforated plate' upstream of the burner (Fig. 6b) does not improve the mixing behavior but changes it to the worse (Fig. 8f). It seems that the turbulence scales generated by the quite small holes of the 'perforated plate' are too small to have an influence in the region where the mixing of fuel and air takes place.

In subsequent tests in an atmospheric test rig, the resulting NOx emissions have been measured under fired conditions for the 'mixer' configuration and without mixer.3

In Fig. 9 the trend of the resulting NOx emissions is shown as a function of the flame temperature (calculated from the stoichiometry). Especially in the range between 1300 and 1650°C, a reduction of the NOx emission of up to 30 % has been found, compared to the standard configuration. Obviously, the better mixing process is really of importance, as was assumed from theory. For very lean mixtures (flame temperature below 1300°C), the influence of advanced mixing on the NOx emission decreases (Fig. 9). It seems that here, connected with the dominance of the prompt NOx formation path, the nonlinear temperature dependency of the NOx formation rate is much weaker than for flames above 1300°C, so that the influence of mixture fluctuations has a minor effect on the resulting NOx emissions.

3 The NOx emission measurements at the atmospheric fired test rig have been performed in a separate investigation at Siemens AG - KWU, confirming the presented investigation of the mixing quality optimization. Therefore some results are shown here, although details of these experiments can not be described.
CONCLUSION

At a constant overall fuel-air ratio, the level of the NO\textsubscript{X} emissions of lean premixed combustors is strongly dependent on the degree of the mixture fluctuations. The two-dimensional technique of laser-induced fluorescence with acetone as tracer of the fuel flow was utilized to investigate the temporally and spatially resolved fuel-air mixing of a real size industrial gas turbine burner. The investigation was conducted as a cold flow experiment and the normalized standard deviation of the fuel-air ratio was determined to evaluate the influence of different configurations on the mixing quality.

The standard configuration shows significant fluctuations of the instantaneous fuel-air mixture, although the mean fuel-air ratio is homogeneous. It is found that a variation of the momentum ratio between fuel and air flow can improve the mixture quality for instance by modifying the diameter of the fuel inlet holes.

A further reduction of the mixture fluctuations can be realized by applying additional turbulence generating mixing elements upstream of the burner. A specially designed 'mixer' improved the mixing quality significantly. On an atmospheric fired test rig, exhaust gas measurements of this lean burning combustor showed a significant decrease of NO\textsubscript{X} especially for flame temperatures between 1300 and 1650°C, when the 'mixer' was installed.

REFERENCES


Steele, R.C., Malte, P.C., Nicol, D.G., and Kramlich, J.C., 1995, "NO\textsubscript{X} and N\textsubscript{2}O in lean-premixed jet-stirred flames", Combustion and Flame 100, pp. 440-449.
