RESEARCH ON CONCEPTS TO REDUCE CO_2 EMISSIONS AT TECHNICAL CONDITIONS

Klaus Peter Geigle, Oliver Lammel, Peter Kutne, Harald Schütz, Rainer Lückerath, Manfred Aigner

Institute of Combustion Technology, German Aerospace Center (DLR), Stuttgart, Germany

Introduction

One key motivation for current gas turbine burner development is reduction of CO_2 emissions as this species is assumed to contribute to climate change. Besides an improvement of combustor efficiency, other approaches are considered to be capable reducing CO_2 emissions such as use of hydrocarbon-reduced or even hydrocarbon-free fuels or oxyfuel combustion allowing for a separation of CO_2 after combustion took place. When leaving conventional combustion schemes, changes of the combustion behaviour have to be considered for future burner designs. Major requirements of new designs are similar or even better efficiency, for example by increasing the turbine inlet temperature, fuel flexibility and low NOx and CO emissions. To support burner development our institute employs high pressure testing in combination with optical diagnostics enabled by good optical access and numerical simulation.

The following sections deal with three main activities on CO_2 reduction that have been accomplished recently: simulation supported burner development based on the flameless oxidation concept, characterization of syngas combustion behaviour and studying parameters influencing oxyfuel combustion.

Enhanced FLOX® burner development

In this section a short introduction into our recent burner development activities is given. It mainly focuses on CFD based geometry optimization leading to ulta-low emissions at high efficiency and relevant power densities when using hydrogen-rich combustion. Flameless oxidation is a promising approach towards low emissions due to its relatively homogeneous combustion [1,2]. Although visual flame emissions do not disappear completely, combustion is spread out in the whole combustor, providing a very minor blue glow at FLOX operation,

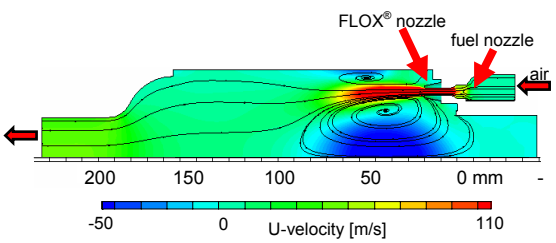
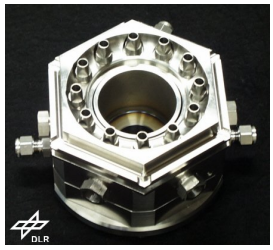


Fig. 1: Illustration of FLOX® operation; the burner axis in this simulation is at the bottom.



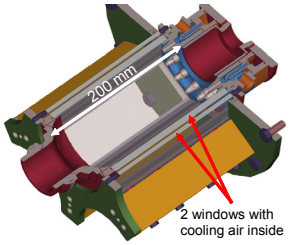
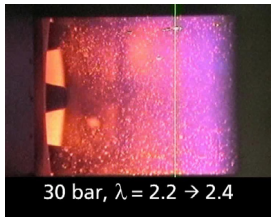


Fig. 2: Experimental realization of DLR FLOX burner V1 for operation up to 30 bars.

typically coinciding with very low pollutant emissions. That is achieved by a high fresh gas inlet velocity required for a pronounced recirculation zone, so mixing exhaust and fresh gases. The fresh gases consist of fuel and air that are already premixed inside the nozzles (Fig. 1).

Initial high pressure experiments up to 30 bars in a hexagonal optically accessible combustor (Fig. 2) have been performed for 2 different nozzle diameters and studying the influence of the inlet velocity on operation. Very low pollutant emissions could be achieved when approaching FLOX operation at very lean conditions (Fig. 3). Following these first experiments, an iteration loop should extend the operation to hydrogen-rich fuels of different composition and even higher power densities.

For doing so we employed numeric simulation. Parameter variations were performed to identify the ideal fuel/air mix nozzle location, number and diameter. Criteria for the optimization were low pollutant emissions at the combustor exit, homogeneous temperature distributions and a high area energy density. To be able to determine reliable species concentrations in the exhaust gas, we employed a relatively large chemical mechanism (GRI 3.0, 325



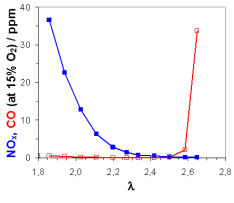


Fig. 3: Very homogeneous flame (FLOX®) avoiding peak temperatures responsible for high NOx emissions (left) and respective emission values (right). Fuel/air nozzles are visible to the left.

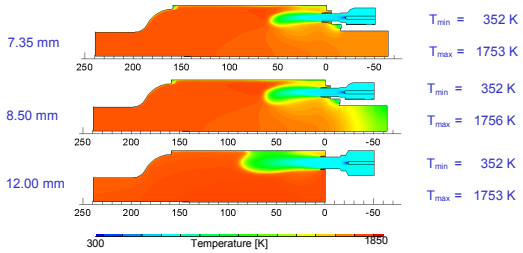


Fig. 4: Simulations of the 12 mm diameter nozzles provided the most homogeneous temperature field and most pronounced recirculation zone when varying this parameter. Given the resulting very low emissions this design was chosen for burner V2.

.

reactions, 53 species), on the other hand keeping the grid size of the calculated 30° segment relatively coarse (8-80k cells), but making use of a hybrid mesh with dynamic mesh adaptation. The plenum was (and has to be) included into the computation grid. Fluent 6.1 (URANS) making use of the $k - \varepsilon -$ turbulence model was used as the basic tool to accommodate our choice of chemistry mechanism. Details about the modelling are provided in [3].

The best suited geometry following parameter variations with CFD (Fig. 4) was selected for a next series of high pressure measurements and a respective burner manufactured accordingly. The improved design only allowed for operation up to 7 bars due to the larger nozzle diameter of 12 mm. Typical gas turbine air inlet temperatures of 400-500 °C were chosen, together with an air mass flow of up to 660 g/s resulting in fresh gas velocities up to 150 m/s. This second sequence of experiments was principally used to study the influence of variations of fuel composition. Up to 100% of the natural gas was replaced by hydrogen. During the tests an increase of the area energy density by an order of magnitude was proven without trade-offs in stability.

For basic flame characterization we employed OH chemiluminescence (OH*) measurements to monitor flame shape (especially homogeneity) and conventional exhaust gas analysis for pollutants.

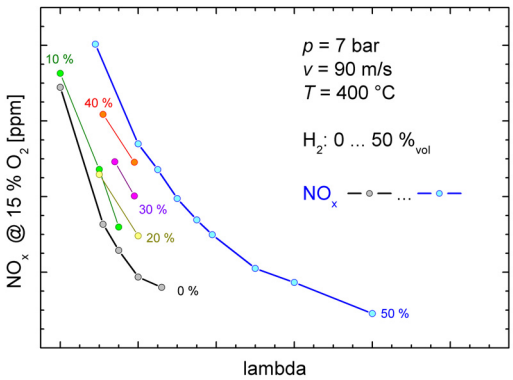


Fig. 5: Extension of the operation range further into the lean regime when replacing natural gas with H_2. Achieved NOx levels for 50% H_2 are very low.

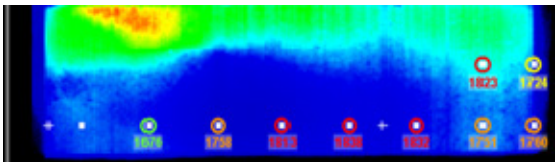


Fig. 6: OH PLIF image with overlaid CARS temperatures measured along the burner axis. A flame area of approx. 20 mm above the burner axis is shown. Bright intensity appears close to the nozzles (left). Statistical temperature data are available at each CARS measurement location.

In addition, pressure sensors provided information on flame stability. However, instabilities known from other burner designs were found to be negligible. As expected, increasing the air excess ratio λ provided more homogeneous OH* images indicating homogeneous heat release. This is typically correlated with decreasing NOx emissions. By addition of H_2 we determined a significant extension of the operating range towards the lean regime at further decreasing NOx emissions (Fig. 5).

More challenging diagnostics were employed to provide a detailed characterization of the combustion behaviour and validation data for our CFD modelling. A very important parameter for validation of combustion simulation is the velocity field that is dominating the quality of the total computations. Main criteria indicating good agreement are the downstream location of the stagnation point and the dimension of the recirculation zone. For both criteria as well as the general flow field appearance the agreement with particle image velocimetry (PIV) measurements under reactive, pressurized conditions is very satisfactory. OH distributions measured with OH laser-induced fluorescence (OH PLIF) show a good general agreement of the qualitative OH concentration field with computations. CARS measurements mainly performed along the burner axis provide statistical information on local temperatures and show relatively uniform mean temperatures and weak fluctuations within the inner recirculation zone (Fig. 7).

Our previous experiments show that the presented burner design can be operated at typical gas turbine operating conditions and has very promising features. Those are fuel flexibility, especially interesting for using H_2 contributions to reduce CO_2, and the capability of very low emissions combined with high area energy density. Optical diagnostics applicable to high pressure combustion and numerical simulation proved to be extremely helpful for design optimization.

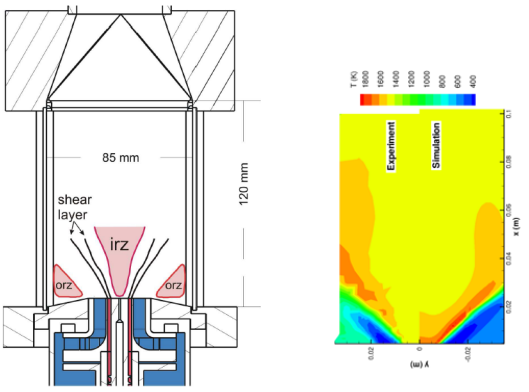


Fig. 7: Burner used for syngas studies up to 10 bars in experiment and simulation (left). Comparison of simulated temperatures and those determined by laser Raman scattering for the 1 bar test case (right).

Characterization of Syngas Flames

Conversion of coal or biomass into syngas allows for efficient use of solid fuels in a combined cycle process and reduction of the carbon content of the fuel during the reformation process. The resulting fuel mixture is a hydrogen rich fuel gas, while the exact composition depends on the production process. However, the combustion behaviour of syngas differs significantly from conventionally used natural gas, and the composition is one major influencing contributor. Very little information is available about the behaviour of syngas mixtures operating under low emission, lean combustion regimes such as in gas turbines. Within German and European projects (HEGSA and VESKO, respectively), we carefully studied different syngas mixtures at atmospheric and increased pressure with optical diagnostics, chemical kinetics and numeric simulation.

Interface of those disciplines was a burner specifically designed for syngas combustion (Fig. 7, left). It is a dual-annular, gaseous fuelled swirl-flame burner with a circular bluff body located along its central axis. The bluff body (Ø = 10 mm) is surrounded by the fuel inlet (Ø = 14 mm) and the annular air nozzle (i.d. = 16 mm, o.d. = 30 mm). The burner was developed at the University of Twente [4] and has been described in greater detail in previous papers [5,6]. The same burner was used before to measure atmospheric syngas flames [6]. For the pressurized experiments (p = 10 bars) the burner was mounted in a combustion chamber with water cooled posts, a cooled front plate, and exhaust section and installed in a high pressure test rig. The chamber measures 85 x 85 mm (cross-section) and is 120 mm tall. The windows for the pressurized experiments were smaller than for the atmospheric experiments, but the inner geometry of the combustion chamber was identical to the atmospheric setup. The syngas mixtures studied had heating values of about 5–6 MJ/m^3 resulting in up to 230 kW thermal power at 20 bars. Main variation parameters besides syngas composition were equivalence ratio and pressure. Details about the experimental results using OH*, OH PLIF and PIV under reactive conditions are described in [6,7] while recent Raman measurements at atmospheric pressure to determine local major species concentrations and temperatures have not yet been published. Fig. 7 (right) shows Raman data in comparison with simulation at 1 bar.

The experimental data have been used for validation of combustion simulation as described in [8]. For this purpose, a detailed finite-rate chemistry combustion model (see Fig. 8) has been employed to investigate fuel composition effects on combustion properties. It has been shown that the numerical models are fundamental both to show main flow features in the combustion chamber and to understand the influence of fuel composition and operating conditions on the combustor's performance. The use of finite-rate combustion and assumed PDF models has enabled the investigation of detailed reaction paths and the inclusion of OH* chemistry. For all measured fuel mixtures the flames burned very stably without exhibiting thermoacoustic instabilities. This is mainly due to the high hydrogen percentage contained in the model fuel, which makes the fast H_2 chemistry predominant and shadows the slow methane decomposition. Although the fuel composition has no influence on the overall behaviour of the flame, the shape and the dimensions are changing with the fuel composition. In particular, the presence of CH_4 enlarges the flame front in the flow direction significantly. The velocity distributions show an excellent agreement with the PIV measurements and assess the validity of the k–ε model even in swirling flows. OH distributions are less well reproduced, but flame angle and position are predicted well. Additional modelling work has to be done in improving the turbulent transport and fluctuation modelling, since these aspects may be the major cause of the observed discrepancies [8].

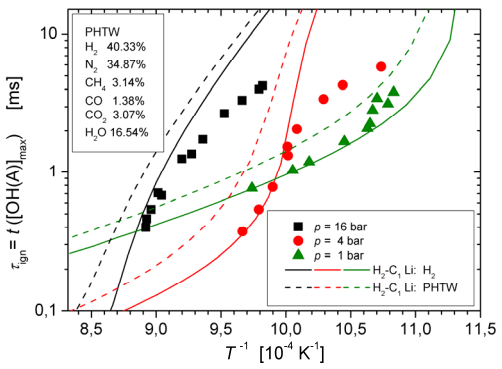


Fig. 8: Different chemical mechanisms, here monitored by ignition delay times, were studied and optimized for implementation into the CFD code used for combustion simulation. For details see [8].

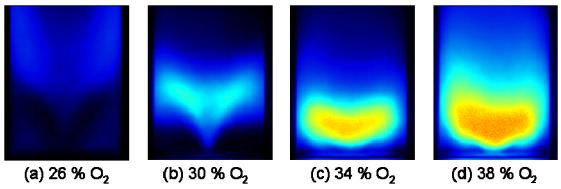


Fig. 9: The images show OH distributions for different oxidizer compositions studied in the burner described in [11]. The influence of O_2/CO_2 ratio for constant equivalence ratio is significant.*

Parameter Study of Oxyfuel Combustion

The third section of this paper contains a short overview of our recent oxyfuel research. In the oxyfuel procedure the fuel is combusted in an atmosphere of oxygen diluted with flue gas and/or steam instead of normal air. This creates a very clean mixture of CO_2 and water as exhaust gas, without the large amounts of nitrogen as air would have brought in. By condensing the water steam, the CO_2 can be separated easily. Two technical challenges shall be mentioned here: the need to separate air in order to provide the required pure oxygen and the need to predict the changes in combustion behaviour related with modifying the oxidizer. While the first issue is left to other research groups, we studied the second one by varying O_2 concentration in the oxidizer, equivalence ratio and thermal power in atmospheric experiments. The described research is part of the BIGCO2 project, performed under the strategic Norwegian research program Climit and having Norwegian Sintef among the partners.

Detailed research of the burner using conventional air to oxidize methane has been published in a number of papers, as well experimentally as theoretically [9-12,13]. So, for the chosen burner an ideal data base exists to compare the current experiments to. Those consisted mainly of stability tests and flame monitoring using OH chemiluminescence as indicator of heat release [14]. Recent 1D laser Raman measurements to determine major species (CO_2, O_2, CO, H_2O, CH_4, H_2) along a line and temperatures one a single laser shot basis are currently being analysed.

Flames could be stabilized over a wide parameter range. The O_2 fraction shows a strong influence on the flame shape due to modified flame speeds (Fig. 9), whereas changes in stoichiometry only have marginal effects. While for 40% oxygen content of the oxidizer the flame speed is similar to CH_4/air flames, levels of approximately 20% are envisaged to meet desired rotor inlet temperatures. Because of significantly different flame speeds, those could not be stabilized without preheating the air. The flame behaviour seems to be quite different from methane air flames at comparable conditions and it is not possible to predict the behaviour under pressurized conditions from these results directly. However, the results will help to plan the experiments under elevated pressure. Supplemented by recent laser Raman measurements they can be used to develop numerical tools for simulation of oxyfuel combustion processes.

References

[1] R. Lückerath, W. Meier, M. Aigner, J. Eng. Gas Turbines Power, 130, 011505-1 - 011505-7 (2008).

[2] H. Schütz, R. Lückerath, T. Kretschmer, B. Noll, M. Aigner, J. Eng Gas Turbines Power, 130, 011503-1 - 011503-9 (2008).

[3] O. Lammel et al., ASME Turbo Expo 2010, 14.-18.06.2010 Glasgow (Scotland) in preparation.

[4] S. G. Pater, J. B. Kok, T. H. van der Meer, Proc. ASME Turbo Expo 2006, GT2006–90910, 08.-11.05.2006, Barcelona (Spain).

[5] M. Tsurikov, W. Meier, K.P. Geigle, Proc. ASME Turbo Expo 2006, GT2006–90344, 08.-11.05.2006, Barcelona (Spain).

[6] P. Kutne, I. Boxx, M. Stöhr, W. Meier, Proc. 3rd European Combustion Meeting 2007, Paper 23-4, 11.-13.04.2007, Chania (Greece).

[7] P. Kutne, R. Sadanandan, W. Meier, Proc. 4th European Combustion Meeting 2009, Paper 174, 14.-17.04.2009, Vienna (Austria).

[8] M. Di Domenico, P. Kutne, C. Naumann, J. Herzler, R. Sadanandan, M. Stöhr, B. Noll, M. Aigner, Proc. ASME Turbo Expo 2009, Paper GT2009-59308, 08.-12.06.2009, Orlando (Florida).

[9] I. Boxx, M. Stöhr, C. Carter, W. Meier, Appl. Phys. B 95, 23 (2009).

[10] I. Boxx, C. Heeger, R. Gordon, B. Böhm, A. Dreizler, W. Meier, Combust. Flame 156, 269 (2009).

[11] P. Weigand, W. Meier, X.R. Duan, W. Stricker, M. Aigner, Combust. Flame 144, 205 (2006)

[12] W. Meier, X.R. Duan, P. Weigand, Combust. Flame 144, 225 (2006).

[13] A. Widenhorn, B. Noll, M. Aigner, Proc. ASME Turbo Expo 2009, Paper GT2009-59038, 08.-12.06.2009, Orlando, Florida.

[14] P. Kutne, B.K. Kapadia, W, Meier, 4th Int. Conf. on Clean Coal Technologies, Paper 3730, 18.-21.05.2009, Dresden (Germany).