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Experimental and numerical study of MILD combustion for gas turbine applications

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HIGHLIGHTS

- Effect of pressure, mixing on stability of MILD combustion studied for gas turbines.
- High pressure increases NO_x emissions and destabilizes MILD combustion mode.
- Enhanced mixing stabilizes MILD combustion and lowers NO_x emission.
- Mixing is key parameter to control and stabilize MILD combustion.

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ABSTRACT

In this paper, the pressure influence on the MILD combustion process and on emissions is examined. Experiments were performed in a combustion chamber based on the reverse flow configuration to enhance mixing of fresh and burnt gases. First, investigations under atmospheric pressure were performed to determine the regime of jointly low NO_x and CO emissions. Afterwards, the effects of burnt gas recirculation and mixing under ambient pressure were evaluated by decreasing the inlet nozzle diameter without changing the residence time. In the second step, measurements were conducted under higher pressure while keeping the mass flow rates constant. Thereby, the residence time is extended, the NO_x formation chemistry is changed. These effects result in a strong rise in NO_x emissions and simulations indicate that at higher pressure a flame is established at the nozzle exit for higher equivalence ratios. In order to decrease the Damköhler number and shift the combustion process to the well-stirred reactor regime, the inlet nozzle diameter was decreased without changing the residence time. Thereby, burnt gas recirculation and gas mixing is enhanced, while simultaneously extending the chemical time scales. A significant decrease in NO_x emissions was detected.

1. Introduction

The stringent regulations on exhaust emissions for gas turbines motivate the development of new combustion technologies in order to achieve low emissions combined with good stability and high combustion intensities. Based on the concept of burnt gas recirculation and hence the dilution of fresh gases, the Moderate or Intense Low oxygen Dilution (MILD)-concept is a promising future technology to reduce emissions of nitrogen oxides as well as carbon monoxide [1]. This concept has been tested in a so called Flameless Oxidation Combustor (FLOXCOM) and has already proven its potential to reduce NO_x emissions [2] in furnace systems under atmospheric pressure. Flameless oxidation has been studied in various furnace systems differing in thermal power output and design [3,4]. While Szegö et al. [3] investigated the turbulent flame structure in a 20 kW single MILD combustor, Cho et al. [4] evaluated the configuration effects of a 200 kW multi-burner furnace on efficiency and emissions.

For the successful application of MILD combustion in gas turbines, the trade-off between efficiency, emissions, and stability is essential. For instance, gas turbine efficiency is primarily related to the turbine inlet temperature, with higher temperatures yielding higher efficiencies [5]. However, NO_x emissions increase exponentially with temperature and linearly with residence time. Concerning CO emissions, increasing the residence time is favorable for CO oxidation to CO_2, and reducing the combustion temperature can increase carbon monoxide by quenching the CO to CO_2 oxidation reaction. Combustion with very high dilution or exhaust gas recirculation and simultaneous preheating can substantially reduce combustion peak temperatures and thereby

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NO_x, while simultaneously showing very good stability behavior, and very low noise and CO emissions.

Besides MILD combustion, several similar concepts based on the principle of preheating and diluting the fresh gases with exhaust gases have been investigated, such as Flameless Oxidation (FLOX) [6,7], High Temperature Air Combustion (HiTAC) [8], Stagnation Point Reverse Flow combustion (SPRF) [9], and Colorless Distributed Combustion (CDC) [10]. While these technologies have commonalities, they are not meant to be the same. The term flameless oxidation is related to the fact that a flame cannot be observed, which is caused by high exhaust gas recirculation rates and distributed combustion with small temperature gradients [6]. SPRF, in contrast, refers to the combustor design, which improves the burnt gas recirculation and results in low NO_x emission without external air preheating and without a MILD combustion mode [11]. HiTAC, on the other hand, is related to the excessive preheating of the combustion air above its autoigniton temperature and can operate both in MILD or non-MILD combustion mode [8]. Compared to HiTAC combustion, CDC is characterized by higher combustion intensity and lower residence times [12]. Cavaliere and de Joannon [1] describe MILD combustion as a subset of HiTAC, where inlet temperature is above the autoignition of the fresh gases and the and maximum temperature increase is below the self ignition temperature of the mixture.

One key aspect for all these technologies is the mixing process of burnt gases, fresh air, and fuel in the combustion chamber, which has to be fast enough to be completed before the combustion process begins [6]. Therefore, different combustion chambers were developed in order to improve the mixing process. A swirl chamber was presented by Khalil and Gupta [13]. In this combustor, mixing is improved by a higher turbulence level. However, the shorter residence time also causes a slight increase of CO emissions. A combustion chamber concept related to the typical design of gas turbines is presented by Lückerath et al. [14] and Sadanandan et al. [15]. In this straight flow configuration, the recirculation of burnt gases into the fresh mixture is achieved by high inlet velocities of air and fuel. In this configuration, low emissions of NO_x and CO of less than 10 ppm are observed at pressures up to 20 bar.

In the present study, in order to enhance the recirculation of burnt gas into the fresh fuel air mixture, a reverse flow configuration is used, where the outlet of burnt gases is in the same plane as the inlet of fresh gases. Similar setups have been investigated by Arghode and Gupta [16] and Neumeier et al. [9]. Arghode and Gupta [16] tested several fuel and air nozzle arrangements in the reverse configuration to evaluate their potential to decrease NO_x and CO emissions. It was found that the same low level of emissions could be achieved as in a straight flow combustor [16].

For the SPRF combustor proposed by Neumeier et al. [9], Bobba et al. [11] studied the stabilizing effect of recirculated burnt gas in a premixed fuel air flow. It was found that the heat release occurs in regions of low velocity and high turbulence [11]. Their analysis of the chemical time scales in the SPRF showed that although good recirculation was achieved for premixed conditions, chemical time scales were too short to achieve distributed combustion in a MILD combustion regime [11]. While the present study also uses a reverse flow configuration, it has a different nozzle design, it operates in a MILD combustion mode, and at higher pressure. Both flow and combustion physics studied here are therefore different.

A parameter directly influencing the entrainment of combustion gases into the fresh gas stream is the nozzle diameter. Sadanandan et al. [15] found that higher inlet velocities lead to lower emissions. They argued that the increased velocities cause higher entrainment of burnt gases into the fresh mixture, which improves conditions for MILD or FLOX combustion. Instead of changing the volume flows for higher inlet velocities, Arghode et al. [17] kept the mass flow constant and changed the nozzle diameters in order to change the inlet velocities. The increase of the nozzle diameter causes a decrease of the incoming gas stream momentum and thereby reduces the burnt gas recirculation. This resulted in an increase of both NO_x and CO emissions [17]. The same strategy is applied in the present paper to increase the burnt gas recirculation.

While mixing is known to be important for MILD combustion, the effect of the degree of fuel air premixing at the combustor entrance on emissions does not show clear trends. In the straight flow configuration by Sadanandan et al. [15], the non-premixed inflow leads to lower NO_x and CO emissions than the premixed case. Arghode et al. [12] showed for their reverse flow configuration that the premixed inflow can achieve lower emissions. Besides the mixing of air and fuel at the chamber inlet, the mixing of fresh and burnt gases in the chamber is important to ensure homogeneous combustion over a large volume, thereby avoiding local temperature peaks causing high emissions of NO_x.

Although combustion in gas turbines occurs at higher pressures, only few studies on MILD or flameless oxidation have been performed under increased pressure so far [14,15]. In the present study, the maximum pressure in the experimental investigations is increased up to 5 bar. However, in order to detect the pressure influence on emission formation up to typical gas turbine pressures, computational fluid dynamics simulations were also performed. The aim of this study therefore remains threefold: (i) Characterize the regimes of jointly very low NO_x and CO emissions at atmospheric pressure in terms of global equivalence ratio (ϕ); (ii) Identify the influence of higher pressure on emissions; and (iii) Determine the dominating mechanisms of NO_x formation by analyzing the effect of residence time, different NO_x formation pathways under higher pressure, and higher burnt gas recirculation.

Towards this end, experiments are performed for varying operating conditions and nozzle geometries, and in addition, OH^*-chemiluminescence imaging and numerical simulations are used to analyze the observed trends and to detect the reaction regions in the chamber.

2. Experimental setup

The presented combustor is a reverse flow configuration based on the design of Plessing et al. [7] and Dally et al. [18], but designed for gas turbine applications. It is also similar to the SPRF combustor [11]. However, in contrast to both combustors, it is built for higher pressures, has a smaller combustor volume, and an improved recessed nozzle design. The experimental setup consists of three parts: ignition chamber, main combustion chamber, and recuperator, as shown in Fig. 1. For the ignition and preheating process, a small chamber with a volume of about 115 cm^3 is located at the top of the setup. Two tubes for air and fuel are mounted as supply for the ignition chamber. The mixture is ignited by a spark plug and the hot combustion gases preheat the main combustion chamber. After reaching temperatures of about 1100 K, air and fuel supply are switched from top to bottom. Fuel and air enter the main combustion chamber through two concentric nozzles located at the bottom of the chamber, resulting in a partially premixed inlet stream as shown in Fig. 2. The diameter of the fuel nozzle is $D_{fuel} = 2$ mm. Air nozzle diameters can be adjusted to $D_{air} = 10$, 6.3, and 4.5 mm in order to vary the exit velocity. The air nozzle exit is 35 mm downstream of the fuel nozzle exit. The main combustion chamber has a square cross-section with a side length of 58 mm and it is about 200 mm long. Three combustor walls are equipped with quartz glass windows (40 × 50 mm) adjustable to different positions to guarantee optical access at all positions along the centerline of the chamber. For temperature measurements,