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Experimental comparison of a 2D laminar diffusion flame under oxy-fuel and air atmosphere

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ABSTRACT

We present an experimental study on the effects of an oxy-fuel atmosphere with $30\,\%_{\mathrm{Vol.}}\ O_2/70\,\%_{\mathrm{Vol.}}\ CO_2$ content on a laminar, non-premixed methane flame based on measured spatial profiles of gas temperature as well as H_2O, CH_4, OH and CO concentrations, with the aim of providing thermochemical validation data for numerical simulations in the oxy-fuel context. The in situ measurements were performed using temporally multiplexed laser spectrometer based on direct laser absorption spectroscopy in combination with two-line thermometry. The system is validated on a well-characterized air-blown flame at the same burner and found to be in good agreement with reference data. The different behaviors of the oxy-fuel compared to the conventional air-blown flame with respect to the flame structure, species concentrations and temperature distribution are discussed and explained by the altered thermo-physical properties of the oxy-fuel atmosphere and the reactions involved. The altered stoichiometry of the oxy-fuel flame leads to increased CO and H_2O concentrations, whereas the increased heat transfer and heat capacity caused a reduction in peak flame temperature.

1. Introduction

The combustion of fossil fuels for power production, in particular of coal and gas with their high carbon content, is one of the major sources of the anthropogenic greenhouse effect through the emission of carbon dioxide (CO_2). Even though the global share of renewable energies on the overall power generation is on the rise, the combustion of fossil fuels continues to grow and will continue to give an important contribution to the energy production [1]. Carbon capture and sequestration (CCS-) processes to allow pre- or post-combustion CO_2 sequestration have gained significant attention in recent years [2]. In these scenarios, the CO_2 is captured, liquefied and stored underground to allow significant reductions of the CO_2 emissions. One promising post-combustion sequestration technique is the oxy-fuel combustion, which is suitable for future coal and/or gas power plants, but also promises an economical alternative for the retrofit of older power plants. During oxy-fuel combustion, the natural atmospheric nitrogen (N_2) in the air is replaced by CO_2 through a partial flue-gas recirculation. Hence, it additionally allows to minimize or even avoid NO_x formation. The loss of oxygen is compensated by injection of pure oxygen (O_2) gas from air separators or liquid O_2 supplies. Under oxy-fuel conditions, the primary combustion products are CO_2 and water vapor (H_2O). As the water vapor can be condensed and removed from the flue gas, the exhaust gas primarily consists of CO_2 [2]. By changing the O_2 content within the oxy-fuel conditions, the adiabatic flame temperature can directly be affected. This has thermodynamic and efficiency advantages over conventional air-blown combustion processes under air atmosphere.

Combustion of fossil fuels under oxy-fuel atmosphere is accompanied by major changes in the combustion behavior. Compared to air combustion, oxy-fuel has an increased molar heat capacity, leading to a lower flame temperature, an increased density and thus higher momentum as well as a lower diffusion coefficients, generating a need for increased O_2 availability [3]. Additionally, the laminar flame speed is decreased due to a reduced thermal diffusivity which leads to flame stability issues. The tri-atomic CO_2 molecules lead to an increased heat flux through radiation in the infrared. Furthermore, in contrast to nitrogen, carbon dioxide is not inert during the combustion as it can react with the fuel to form CO at stoichiometric flame temperatures.

To account for these additional effects and subsequently model, describe and predict the technical oxy-fuel combustion, computationally efficient and accurate numerical models have to be adapted, extended or even newly developed. Additionally, the new models have to be simplified for an economical simulation and the numerical simulations need to be validated via experimental data. Thus, flames under air

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and oxy-fuel conditions need to be realized and compared. In order to separate technical realization problems from numerical and experimental characterization simple, generic, laminar flames are preferable for model-experiment comparison. For both oxy-coal and oxy-gas combustion in gas turbines, a model fuel is necessary. Methane flames are favorable, as the underlying chemical reactions are well known and easier to describe compared to more complex fuels, especially solid fuels such as coals. Various measurements can be found in literature on temperature [4], flame structure and mixture fraction [4], radiative heat flux and flame height [5], flame speed [6,7] and soot formation [8] of methane oxy-fuel combustion in laminar, premixed Bunsen [6], laminar flat-flame [8], laminar premixed ignition-chamber [7], laminar non-premixed jet [5] and turbulent swirl [4] burners. However, detailed investigations of the temperature and species concentrations of generic laminar, non-premixed oxy-fuel flames with well-known boundaries for a model validation using numerical simulations are to our knowledge still highly absent.

To fill this gap, we present quantitative species concentration and temperature measurements of a 2D methane flame under oxy-fuel atmosphere with 70 %$_{\text{Vol.}}$ CO_2 and 30 % $_{\text{Vol.}}$ O_2 content (OXY30). The flame is generated by a Wolfhard-Parker burner, due to its simplicity, stability and the availability of a comprehensive set of reference data for a flame operated under air atmosphere. Additionally, due to symmetry of the burner, the dimensionality of a numerical simulation can be reduced to a 2D description of one half-plane of the burner, to significantly save computational costs. The reference data measured for conventional air-atmosphere is used for verification of the new measurement system. This spectrometric measurement system is designed to measure the temperature of the flame in different lateral positions and heights in combination with concentrations of the flame educt species CH_4, the intermediates OH and CO as well as the product species H_2O. It consists of four fiber-coupled diode-lasers in the near infrared region. Three of the lasers are time-multiplexed at a repetition rate of 330 Hz and superimposed in a single multi-color beam to analyze the flame. A fourth laser is utilized separately to measure CO at the same repetition rate. The multi-parameter spectrometer employs direct tunable diode laser absorption spectroscopy (TDLAS) to allow absolute species and temperature measurement in the flame without gas sampling.

First, the measurement principle, the spectrometers and the burner will be explained in more detail. Secondly, a comparison between reference data of a flame under air atmosphere and measured results of the spectrometers will be given. Afterwards, new results of the combustion under oxy-fuel atmosphere will be shown and discussed.

2. Experimental setup

2.1. Wolfhard-Parker burner

For the experiments, a Wolfhard-Parker-type (WHP) burner, originally described by Wolfhard et al. [9] for ethylene-oxygen flames, is used in the improved design by Smyth et al. [10,11] and Wagner et al. [12] for methane-air flames, who stabilized the flame by introducing a second oxidizer slot. The investigated flames are laminar and non-premixed. As can be seen in Fig. 1, the burner consists of three parallel slots of 40 mm length, with the central slot ejecting methane and the outer ones providing oxidizer (either air or OXY30). The flow is homogenized using a settling chamber filled with silica beads inside the burner and a copper wire mesh on top of it. The rectangular slots provide a planar, quasi-2D flame with two flame-sheets, creating a 41 mm absorption path for the laser that is homogeneous along the slot axis (y-direction). At the end of the methane slot, the burner is equipped with two slots (design by Wagner et al. [12]) for purging with N_2 during air operation and CO_2 during combustion with oxy-fuel atmosphere. This prevents edge flames at the slot tips as well as a stretch of the flow along the y axis due to expansion. The flame sheets are stabilized using a wire screen chimney above the burner as well as screens in the far-field around the burner to prevent disturbances by air drafts. The burner is automatically traversable in x-z direction. Using the translation stage, measured profiles are taken along the lateral (x-) axis at different heights (z-axis).

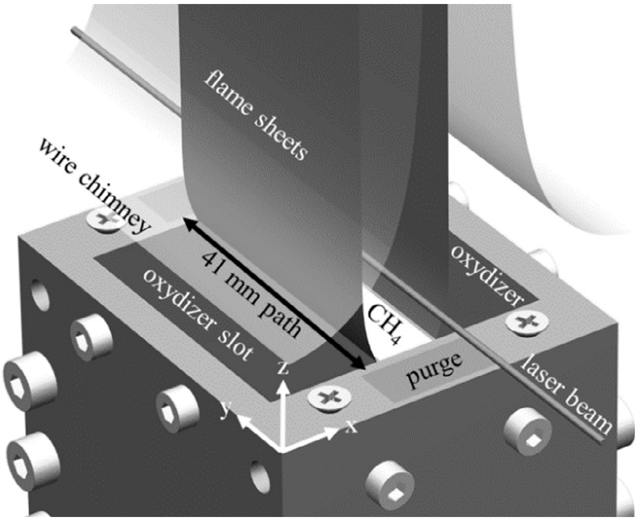

Fig. 1. Setup of modified Wolfhard-Parker burner.

The operating conditions of the burner under air atmosphere are identical to previous measurements [10–15] and summarized in Table 1. During operation under oxy-fuel conditions, the exit velocities of the oxidizer and purge slots have to be decreased by 50% due to the reduced laminar flame speed and diffusion as well as the increased heat capacity. To reduce the strain rate, the exit velocity of the methane slot is decreased by 40%. Generally, oxy-fuel combustion tends to reduce the range of stable operation in terms of flow velocity, as the flame is either blown away due to the reduced laminar flame speed or the copper wire mesh is significantly heated due to increased heat transfer through radiation from the oxy-fuel flame. Both effects have to be avoided, as the heat transfer from the flame to the mesh is quite complex to model. A stable operation was achieved using an oxy-fuel combination with a 30 %$_{\text{Vol.}}$ O_2/70 %$_{\text{Vol.}}$ CO_2 atmosphere (OXY30) and the operating conditions summarized in Table 1. For lower volume fractions of oxygen, a stable flame could not be established due to the effects described.

2.2. Measurement principle

Multiple spectrometers based on direct tunable diode laser absorption spectroscopy (TDLAS) are established for the non-intrusive, in situ species and temperature measurements. TDLAS is often used in combustion diagnostics, as it can be set up to provide calibration-free, quantitative measurements of temperature and gas species concentrations [12,15,16]. However, in oxy-fuel environments it has been rarely used [17,18], TDLAS measures the resonant and non-resonant wavelength-dependent laser light losses through the flame. In gaseous environments, the wavelength-dependent absorption is caused by near-infrared vibrational-rotational transitions of the gas molecules. These

Table 1
Slot exit velocities for the two different operation cases.

Case	Slot		
	Central (CH_4)	Oxidizer	Purge (N_2 or CO_2)
Air	11 cm/s	22 cm/s	22 cm/s
OXY30	6.5 cm/s	11 cm/s	11 cm/s