Temperature Dependency of the Laminar Burning Velocity of Fuel-Rich Methane Oxygen Measurements

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Abstract

First experiments to determine laminar burning velocities of methane-pure oxygen mixtures were carried out in 1932 by Jahn [1] for a wide range of equivalence ratios Φ (0.2 to 2.64) using a Bunsen burner. Since then, new and most important more accurate methods were developed to determine laminar burning velocities. One of these methods, namely the Heat Flux Method, which was introduced by de Goey et al. [2] in 1993, was used in the current work to validate the results for fuel-rich methane oxygen mixtures (Φ = 2.38 to 2.64) as published by Jahn. Regarding the current Heat Flux Bruner setup the range of velocities that can be determined are limited between 9 and 50 cm/s, which also limits the range of investigated equivalence ratios (Φ = 2.38 to 3.03), which is wider as the one investigated by Jahn [1]. Furthermore, the influence of the pre-heating temperature was also investigated by a variation of it from 263 up to 455 K. Based on these experimental data the temperature dependency of laminar burning velocities of fuel-rich methane oxygen mixtures was determined and as a result the coefficient α of the power law correlation $S_L = S_{L0}\,(T/T_0)^{\alpha}$ was calculated. Due to the increase of the laminar burning velocity at higher pre-heating temperatures, the laminar burning velocities could also be determined at equivalence ratios up to a maximum value of Φ = 3.33 (T_P = 455 K). The increase in accuracy of measurement methods to determine laminar burning velocities over the last decades [3] leads to an observed decrease in measured flame speeds. This tendency is confirmed in the current experiments, where the determined laminar burning velocities are lower than the ones measured by Jahn [1]. Regarding the temperature dependency of the laminar burning velocity, the results indicate that for the range of investigated equivalence ratios and temperatures (300 K to 455 K) the power law coefficient α was observed to be almost constant.

1. Introduction

The production of synthesis gases of various compositions through combustion of premixed, fuel-rich methane oxygen mixtures is applied industrially since the 1950s [4]. The laminar burning velocity is a key parameter for such processes describing the physico-chemical interactions in combustion systems and is also used in turbulent combustion models [5]. Laminar burning velocities of methane and pure oxygen mixtures were experimentally determined as early as 1932 by Jahn [1] in a wide range of equivalence ratios (Φ = 0.2 - 2.64). Especially for the fuel rich side, there are no newer data available in the literature, to the author's knowledge. The measurements by Jahn were performed utilizing a premixed laminar flame in a Bunsen burner. Due to the imperfections of the flow field and the imprecise flame shape and its determination, especially at flame tip and edges, this method is limited in accuracy [6]. There are three different methods to evaluate a Bunsen flame and determine laminar burning velocities. In these methods the visible edge, the Schlieren edge or the inner shadow cone are used for the determination of flame speed by dividing the volume flow rate with the area of the flame cone [6]. Because these flame patterns have different positions inside the flame, also the flame cone area and the calculated laminar burning velocities differ, when using different evaluation methods.

Nowadays, new and more accurate methods are available for determining laminar burning velocities. In 1993 de Goey et al. [2] introduced a method based on a flat flame burner with balanced heat flux between the flat flame and the flat burner support. This method was used in the current work to validate the results for fuel-rich methane oxygen mixtures (Φ = 2.38 to 2.64) as published by Jahn and for extending the range of experimental data in the fuel rich side to higher pre-heating temperatures and also to even higher equivalence ratios up to Φ = 3.33.

Regarding the utilized Heat Flux Burner setup, the flame velocity range that can be accurately determined lies between 9 and 50 cm/s, due to flow control issues at the low end and increased wake effects distributing the flame sheet homogeneity at the upper end. These circumstances consequently limit the range of investigated equivalence ratios (Φ = 2.38 to 3.03 at T_P = 300 K and ambient pressure). The setup was extended by a heat exchanger system enabling to vary the pre-heating temperatures T_P of the premixed gas from 263 K up to 455 K. Thus, the temperature dependency of laminar burning velocities of fuel-rich methane oxygen mixtures could be investigated in the current work.

2. Experimental setup

At the Division of Combustion Technology of the Engler-Bunte-Institute (EBI-VBT), a flat flame burner system based on the Heat Flux Method [3] was built.

2.1. Test rig

The flat flame burner system was adapted from the system described by de Goey and Bosschaart [3] and is

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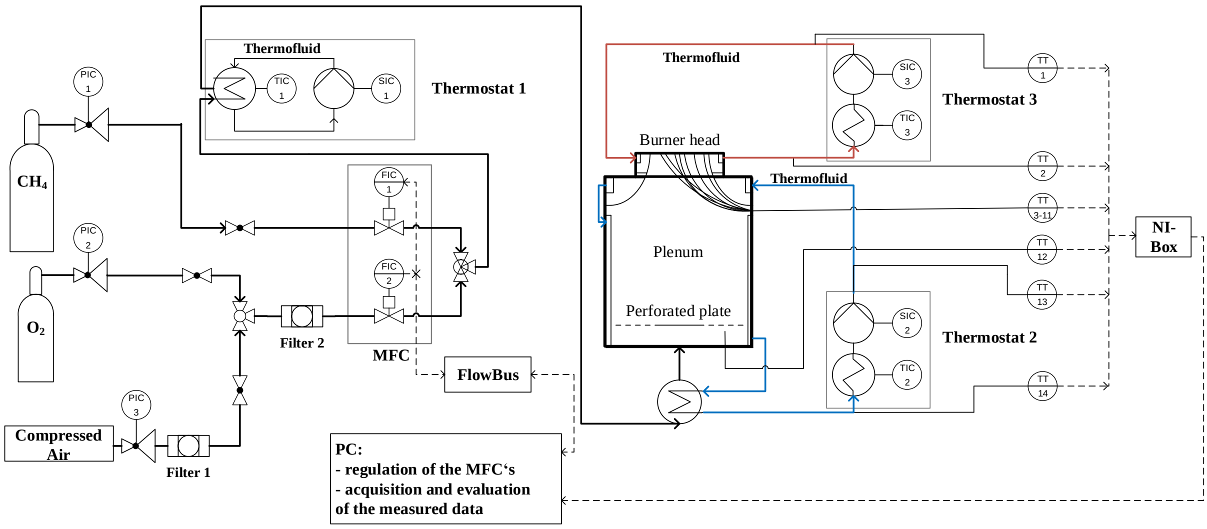

Figure 1: Piping and Instrumentation Diagram of the Test rig

shown in Figure 1. A crucial point for the design of the test rig was to supply accurately mixed fuel-rich mixtures to the burner. To accomplish this task, cylinders with technical methane and oxygen (50 l, 200 bar) were used for the gas supply and additionally the option to use compressed air instead of pure oxygen was provided. Two closed loop mass flow controllers (MFC, Bronkhorst High-Tech, model: EL-FLOW select) were installed for controlling the mass flows of methane and oxygen. Fuel and oxidizer were mixed via a T-mixer and subsequently conditioned (see subsection 2.2). Inside the plenum a perforated plate was placed above the inlet to evenly distribute the premixed gases. On top of the plenum the mixture flow was guided through the burner plate (see subsection 2.3) and a flat flame was stabilized in the downstream vicinity of the plate.

A total of 13 thermocouples (Type T) were integrated into the test rig. Four of them were located at the in- and outlet of the burner plate heating circuit and the temperature control circuit of the plenum, respectively. Eight thermocouples were distributed spirally across the burner plate. The position of those thermocouples was adapted from the approach of Hermanns [7]. A further thermocouple was placed inside the plenum measuring the actual preheating temperature of the premixed gas.

The MFCs and the thermocouples were controlled by a LabVIEW program, in which the set-points of the MFCs can be adjusted, while the temperatures of each thermocouple are acquired, displayed, further processed and recorded.

2.2. Preheating system

In order to reach preheating temperatures of up to 455 K, a preheating system was installed, which can be subdivided in two parts.

The first part consisted of a coil tube heat exchanger placed in an oil bath of a thermostat (Figure 1 Thermostat 1), able to condition the preheating temperature of the gas mixture.

The second part is a modified temperature control circuit of the plenum of the Heat Flux Burner (Figure 1 Thermostat 2). This circuit was extended by an additional heat exchanger at the entrance to the plenum. The thermo oil enters the temperature control circuit at the top of the plenum and exits at the bottom of the additional heat exchanger. This subsystem is used to keep the preheated gas mixture at the desired constant temperature on its way from the exit of the coil tube heat exchanger to the burner plate.

2.3. Burner head

The burner head of the Heat Flux Burner, which is integrated in the test rig, differs from the initial geometry by van Maaren [8] and the improved geometry by Bosschaart [9] and is shown in Figure 2. It consists out of three single parts.

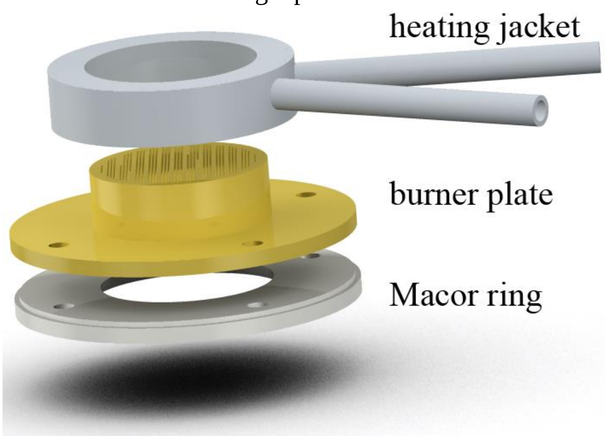

Figure 2: Parts of the burner head

A Macor ring was used to thermally decouple the burner head from the plenum construction. The temperature of the burner head was adjusted at approximately 80 K higher temperature as the plenum. The main difference to the designs from literature consists in the burner plate and heating jacket. In case of the proposed geometry from literature [3, 9] the burner plate is fixed in a supporting structure, in which the heating jacket is integrated. This leads to a non-uniform temperature distribution in the burner plate as shown by Bosschaart [9].

A different approach was taken in the current work to face this circumstance. The burner head still consists of two parts, but they are differently arranged. Supporting structure and burner plate form the first part, which is made out of one single part of brass. The second part is the heating jacket made out of stainless steel. Both parts are provided with a thread and screwed together.

Another difference is the flow pattern of the thermo oil around the burner plate. Whereas in the proposed geometry in [3, 8, 9] the holes for the in- and outlet have an offset of 180°, they are only separated by 30° in this case. This prevents possible flow distribution instabilities.

3. Experimental results

To validate the performance of the new Heat Flux Burner setup, measurement series with methane air mixtures at different equivalence ratios from $\Phi = 0.7$ to $\Phi = 1.4$ at a preheating temperature $T_P = 300$ K and ambient pressure were performed. The results are shown in Figure 3 (black squares) and compared to other published values for the Heat Flux Method [10].

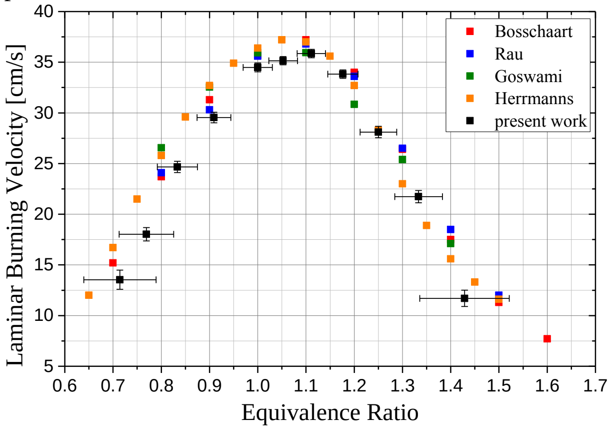

Figure 3: Laminar burning velocities of methane air mixtures at T_P = 300 K and ambient pressure

As shown in Figure 3, the results are well within the range of the published data demonstrating a well working Heat Flux Burner system. However, a systematic deviation showing lower laminar burning velocities in comparison to other heat flux burner systems for lean mixtures ($\Phi < 0.9$) seems to be present and should be mentioned.

In the next step the laminar burning velocities of fuel-rich methane oxygen mixtures at different equivalence ratios from $\Phi = 2.38$ to $\Phi = 3.33$ and preheating temperatures form $T_P = 300$ K to $T_P = 455$ K were determined.

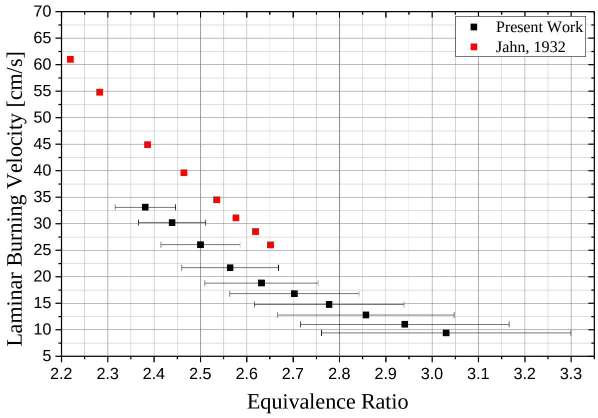

Figure 4: Laminar burning velocities of fuel-rich methane oxygen Mixtures at T_P = 300 K and ambient pressure

The determined laminar burning velocities at a preheating temperature of $T_P = 300$ K are compared with the ones by Jahn in 1932 (see Figure 4). Whereas Jahn could only determine laminar burning velocities for a maximum equivalence ratio of $\Phi = 2.65$, it was now possible to quantify laminar burning velocities for even higher equivalence ratios (up to $\Phi > 3.00$) using the Heat Flux Method. Furthermore, the results show that the laminar burning velocities are up to 25 % lower than formerly published values in this fuel-rich oxy-fuel case.

Figure 5 illustrates the results of the five measurement series which were performed. A comparison of the results of the lowest ($T_P = 300$ K) with the ones of the highest ($T_P = 455$ K) preheating temperature highlights that not only the laminar burning velocity is increasing with a higher temperature, but also the slope of the dependency of the equivalence ratio slightly increases.

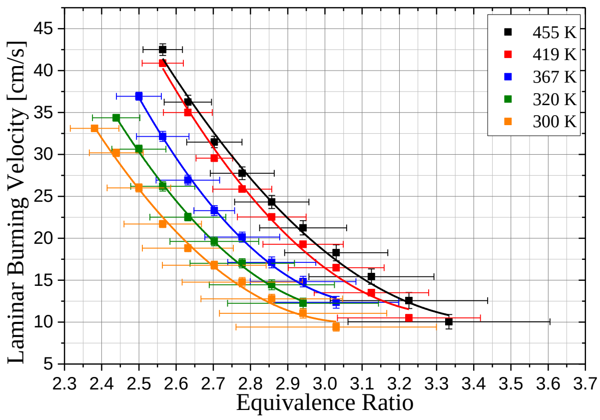

Figure 5: Laminar burning velocities of Fuel-rich methane oxygen mixtures at different preheating temperatures and ambient pressure

In order to determine the temperature dependency of the laminar burning velocity of fuel rich methane oxygen mixtures, the coefficient α of the power law correlation $S_L = S_{L0} (T/T_0)^\alpha$ [11, 12] was calculated.

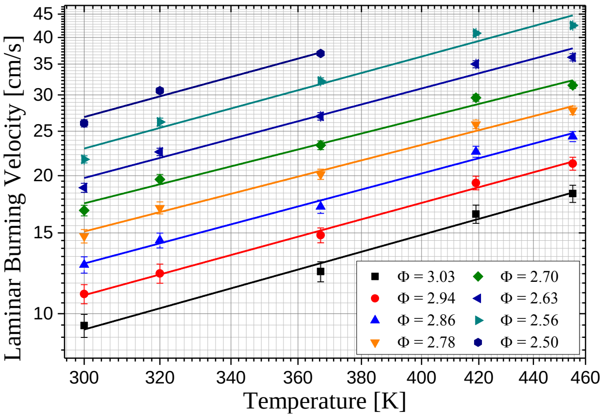

Figure 6: Double logarithmic diagram of laminar burning velocities of investigated equivalence ratios at different preheating temperatures

As a result, in Figure 6 laminar burning velocities for different equivalence ratios (from Φ = 2.50 to Φ = 3.03) are plotted against the preheating temperatures and power fits are applied (straight lines). The coefficient α of the power law correlation is equivalent to the slope of each of the eight fits shown in Figure 6. The resulting coefficient α is assessed to be constant within the confidence interval of the measured values with a value of $\alpha = 1.57$, for the investigated range of equivalence ratios and preheating temperatures as illustrated in Figure 7.

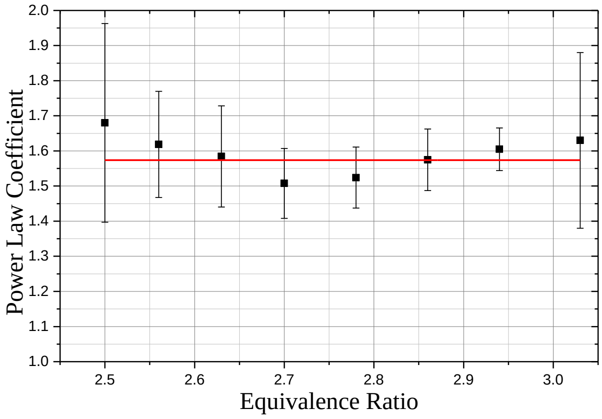

Figure 7: Determined power law coefficients α at investigated equivalence ratios

4. Error estimation

The uncertainty of each measurement is calculated by considering the deviation of the MFCs and the height of the thermocouples in the burner plate and their measuring accuracy as proposed by de Goey [3].

4.1. Deviation of the MFC

At the beginning of each measurement series the accuracy of the MFCs was determined using a reference flowmeter (BIOS, model: Definer 220). These measurements indicated that the maximum deviation for the methane MFC and oxygen MFC are 0.8 % (Δ_{CH4} = 0.2 l_N/min) and 1 % (Δ_{O2} = 0.05 l_N/min) of the maximum flow respectively.

The uncertainty of the MFCs affects the results in two ways. The gas velocity derived from the measured mass fluxes of the MFCs is not exactly the flow-velocity at the burner. Furthermore, the different deviations of the two MFCs result in a difference between the set and actual equivalence ratio.

4.2. Uncertainty of the thermocouples

The eight type T thermocouples that are placed in the burner plate have an influence on the calculated laminar burning velocities. The measuring inaccuracy of each thermocouple is assumed to be σ_{TC} = ± 0.5 K. The position of the thermocouples inside the burner plate also affects the measurement, as explained in detail by Bosschaart [3, 9].

4.3. Calculation of the measuring error

For the maximum deviation of the equivalence ratio only the MFCs have to be considered. The error bars are calculated from the individual volumetric flows by using the following equation:

$$\Delta\Phi = \sqrt{\left(\frac{\partial\Phi}{\partial\dot{V}_{CH4}} * \Delta_{CH4}\right)^2 + \left(\frac{\partial\Phi}{\partial\dot{V}_{O2}} * \Delta_{O2}\right)^2}$$

with $\dot{V}$ the adjusted volumetric flows and Δ the maximum deviations of each MFC.

For the error in the calculated laminar burning velocities Δ_{sl} both, the MFCs and the thermocouples have to be considered.

$$\Delta_{sl} = \Delta_{sl,MFC} + \Delta_{sl,Therm}$$

The error of the MFCs $\Delta_{sl,MFC}$ is calculated by using the maximum deviation of each MFC:

$$\Delta_{sl,MFC} = \frac{\Delta_{CH4} + \Delta_{O2}}{A_{Burner}}$$

A_{Burner} is the cross sectional area of the burner plate. To determine the error in the laminar burning velocity $\Delta_{sl,Therm}$ caused by the different heights of the thermocouples inside the burner plate, at each radial position, the following equation, which was proposed by de Goey [3], was used.

$$\Delta_{sl,Therm} = \frac{1}{s} * \frac{\sigma_{TC}}{r_{TC}^2}$$

s is the sensitivity of the measurement, σ_{TC} the measuring inaccuracy and r_{TC} the outermost radial position of a thermocouple.

5. Conclusions

For the first time the Heat Flux Method was applied to determine laminar burning velocities of fuel-rich methane oxygen mixtures. Due to an extension of the test rig by installing a preheating system the temperature dependency could be investigated too.

In the considered range the determined laminar burning velocities are lower than the published data by Jahn [1]. Regarding the temperature dependency of the laminar burning velocity of fuel-rich methane oxygen flames the results show an approximately constant coefficient $\alpha = 1.57$ of the power law correlation.

The influence of the diffusion flame on the measurements still has to be investigated.

6. Acknowledgement

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