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Application of lean premixed prevaporized burner for renewable fuels

Thesis booklet by
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1 Objective and outline

The fossil fuel utilization is continuously growing, and the climate change correlates with that. These facts made it clear that significant efforts have to be made to reduce the growth of carbon dioxide emission and achieve a sustainable economy through carbon neutrality. Adding renewable fuel to the commercial diesel oil in the European Union is obligatory. This is covered by transesterified rapeseed oil while other vegetable oils are used for a similar purpose in the rest of the world. Hence, the present work investigates primarily the utilization of crude rapeseed oil which is more competitive with the conventional fuels while the transesterification process is skipped. Crude vegetable oil combustion requires a steady operation, therefore, the potential applications are, e.g., boilers, furnaces, and gas turbines.

Regardless of the origin of the fuel, continuously stringent decrees and standards maximize the allowed pollutant emission. In order to be in line with the corresponding limitations, lean combustion is widely applied today. It means that excess air is present in the combustion chamber beside the required amount for stoichiometric conditions. Therefore, the combustion will be complete as there is enough oxygen to burn the fuel. The remaining air reduces the overall combustion temperature due to its heat capacity, hence, reduces the NO_x emission. The key steps of liquid fuel combustion are summarized in Fig. 1.

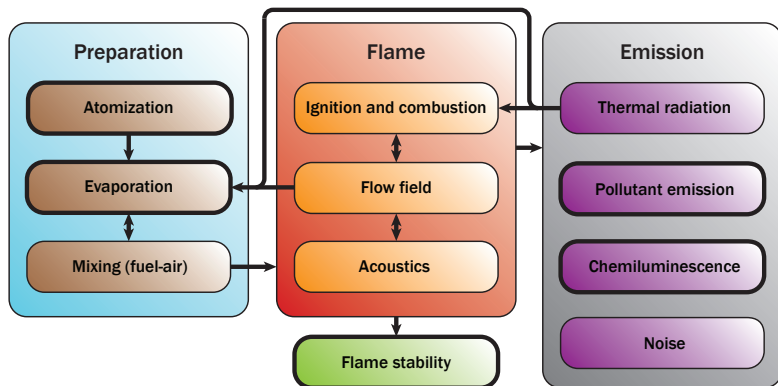


Figure 1: Primary mechanisms and their relation of premixed combustion. Thick borders indicate the investigated phenomena.

Phenomena marked with thick border are investigated in the thesis. The process starts with atomization which ensures low enough droplet sizes. These evaporate and mix with the combustion air before reaching the flame front.

Appropriate mixing is crucial to eliminate the hot spots which can lead to progressively increasing NO_x emission. The combustion process starts with the ignition of the fuel which is largely determined by the flow field and the fuel properties. If the burning velocity is higher than the flow velocity, the flame flashes back and may damage the burner. If the flow velocity is higher, the flame blows out. Due to inappropriate design, acoustic-originated oscillations may damage the combustion chamber. The term emission is not restricted to the pollutants. It also includes the radiative heat transfer to the combustion chamber walls, the chemiluminescence emission, and the combustion noise. The burner which was investigated is a lean premixed prevaporized (LPP) type, shown in Fig. 2.

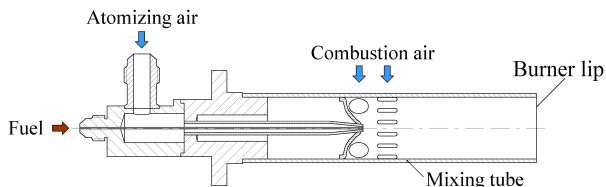


Figure 2: The investigated LPP burner.

Here, a plain-jet airblast atomizer was used for atomizing the fuel. This process can be properly described neither analytically nor numerically. Therefore, the literature contains various empirical and semi-empirical formulas to estimate the volume-to-surface diameter or Sauter Mean Diameter, SMD , while this is the most relevant spray parameter from evaporation point of view. Here comes the first goal of the thesis: comparing various SMD estimating formulas with the measurement results of the used plain-jet airblast atomizer.

However, operating highly lean is attractive from pollutant emission point of view, combustion stability issues arise in parallel to that. Using much diluting air leads to flame blowout as the flow velocity overcomes the burning velocity. Therefore, the swirl is used to extend the operating limitations. The rectangular inlet ports in Fig. 2 are 45° swirl vanes. If the swirl is strong enough, an inner and an outer recirculation zone (IRZ and ORZ, respectively) are formed above the burner lip, shown in Fig. 3. The ORZ can be 'filled' by solid material, resulting in a subsequent diffuser geometry. However, the appearing boundary layer on the wall of the diffuser affects the blowout stability of the burner.

To date, variable loading receives increasing attention in numerous combustion applications including energy production. Fulfilling emission limitations is obligatory at partial loading, as well as it is at full load. Therefore,

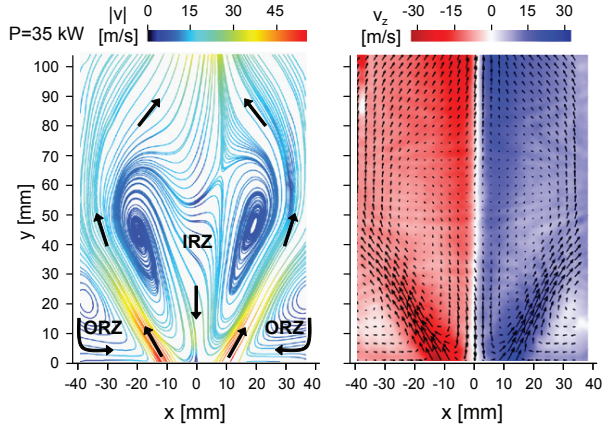


Figure 3: IRZ and ORZ of a V-shaped flame at 35 kW combustion power, indicating the absolute velocity (left) and the tangential velocity (right) [1].

appropriate combustion control becomes highly relevant. The spectrometer is a potential device for this task which can withstand the harsh industrial environment, requires only optical access, and provides real time data for the control system. Hence, the last part of the investigation is the analysis of the chemiluminescence emission of rapeseed and diesel oil flames.

2 Methods

The atomization measurements were carried out by using a Phase Doppler Anemometer under cold conditions, i.e., without combustion. The mixing tube of the burner, shown in Fig. 2, was removed to isolate atomization from other effects. The spray was found to be axisymmetrical, and it was investigated at four diameters at 10, 15, 26.7, and 50 mm axial distances. The atomizing gauge pressure, p_g , was varied between 0.3 and 3.1 bar in nine steps. The data was collected until 20,000 individual particles were measured or 15 s passed. The temporal condition becomes necessary in the analysis of the peripheral region where the spray is more dilute. Then the SMD was determined at each measurement point. The spray was considered as developed at 50 mm axial distance. Therefore, the first thesis is stated based on these results using the data of all the investigated atomizing pressures and all the measured data at this axial distance.

The burner is characterized by a straight flame if the swirl intensity is low. To increase the swirl number, the combustion air flow rate was increased

at a fixed atomizing pressure. Hence, the flame opens to V-shape. Before reaching this state, a bistable regime can be found where random transition occurs between the two flame shapes. Based on the actual conditions, that shape can be observed for a longer time on average which stable form is closer. The measurements started at low combustion air flow rates and continuously elevated. Consequently, the flame was straight at the beginning then entered to the bistable regime. The V-shaped flame was achievable only in certain cases while it was blown out in the bistable regime at typically high atomizing pressures. Beside the rotameters which measured the combustion and the atomizing air flow rate, normal and high-speed videos were recorded at 30 and 480 frames/second, respectively. It allowed the comparison of blowout mechanism of the original burner with that by using subsequent diffusers on the burner lip which lead to the second thesis.

In flame emission spectrometry, the investigated spectrum was 260–580 nm. In this range, the most significant chemiluminescence emitters are OH^* at 310 nm, CH^* at 431 nm, and C_2^* at 516 nm, where * notes the excited radicals. The ratio of the chemiluminescence emission peaks is proportional to the local air-to-fuel equivalence ratio. This analysis was carried out for both diesel and rapeseed oil combustion. It was turned out during the spatial investigation that the strongest signal is located at the axis just above the burner lip. The measurement strategy was the following: the combustion air flow rate was increased in fixed steps until flame blowout while the atomizing pressure was kept at constant. Then this sequence was repeated several times at various atomizing pressures. The systematic measurements, which lead to the third and the fourth thesis, consist the chemiluminescence intensity ratio of the mentioned radicals in the function of air-to-fuel equivalence ratio.

3 Results and theses

Equation 1 is the most widely recognized formula in the spray literature for estimating the *SMD* for plain-jet airblast atomizers.

$$SMD/d_0 = (AWe_A^{-0.5} + BOh_L)(1 + 1/ALR), \quad (1)$$

where d_0 is the initial liquid jet diameter, We_A is the Weber number based on the properties of the atomizing air, Oh_L is the Ohnesorge number based on the properties of the liquid, and ALR is the air-to-liquid mass flow ratio. A and B are constants. It was derived by Lefebvre [2] by using vast amount of measurement data of various airblast atomizer configurations. Therefore, using Eq. 1 to the presented burner do not restrict the validity of the results to a single atomizer geometry. Moreover, the determined constants agreed very

well with the results of Rizk and Lefebvre [3] who used a different atomizer design and a slightly modified version of Eq. 1. While $p_g = 0.01 - 0.2$ bar was used for deriving Eq. 1, the goal was to extend the range of validity of this formula to high-velocity atomization (i.e., $p_g = 0.3 - 3.1$ bar) using diesel oil.

Heng et al. [4] contributed to the atomization literature considerably while they had the opportunity to publish the measurement results of a gas turbine combustion chamber under cold flow conditions, using an airblast atomizer. Ambient pressures up to 12 bar were investigated. Their conclusion was that the *SMD* does not depend on the ambient pressure if the proper dimensionless numbers match. Consequently, the below-presented thesis is not confined to ambient conditions.

Varga et al. [5] concluded that $SMD \sim We^{-1/2}$ at high-velocity atomization based on their measurement results. This finding was preceded by the theoretical work of Lefebvre [6] who stated that the role of viscosity vanishes if the atomizing velocity is high while there is not enough time for the viscosity to affect the breakup process. Based on these findings and the measurement data, the following thesis summarizes the contribution of estimating the *SMD* at high-velocity atomization:

1. Thesis

In the case of plain-jet airblast atomization of standard diesel oil, the following formula estimates the volume-to-surface diameter, *SMD*, of the spray in the range of Mach number, $Ma = 0.6 - 1.6$ and air-to-liquid mass flow ratio, $ALR = 0.78 - 2.3$:

$$SMD = 0.66d_0 We_A^{-0.5} (1 + 1/ALR),$$

where d_0 is the diameter of the liquid jet and We_A is the Weber number based on the properties of the atomizing air. [P1-P3]

Based on the measurement data, it turned out that the application of appropriate diffusers considerably extends the blowout stability of the burner. E.g., diffusers with half cone angle of 15° and 30° provided a 42% increase compared to the original configuration. Therefore, the background phenomenon was filmed. The results are summarized in Figures 4 and 5 based on 30 frame/second videos. These sequences represent the original burner and the application of a 45° diffuser.

The first frame of both figures shows the flame 1 s before the flame blowout. The remainder represents the last five frames in which the flame was observable. It became clear that the flame lifts up, and the reactions stop in the original case. This is the classical blowout where the flow velocity overcomes the burning velocity. Hence, the flame stability cannot be provided further.

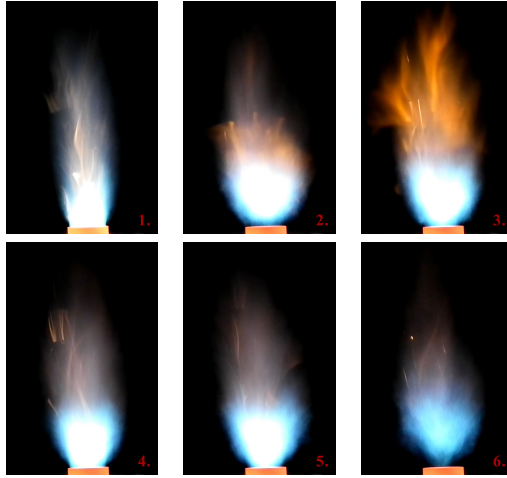


Figure 4: Sequences from the blowout in the case of the original burner, $p_g = 0.7$ bar.

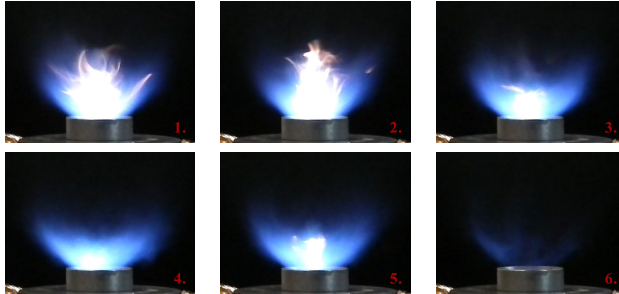


Figure 5: Sequences from the blowout with a 45° diffuser, $p_g = 0.7$ bar.

Regarding the diffusers, they substitute the ORZ. Therefore, the V-shaped flame occupies the allowed space and extends to the diffuser wall. However, a boundary layer is established near the wall where the flow velocity is lower than it is in the main flow. Hence, the flame can be blown out at higher combustion air flow rates as the boundary layer still provides stable combustion which ignites the mixture in the center where the flow velocity has already overcome the burning velocity. This is the reason why the last frame of Fig. 5 shows that the last traces of the flame are located near the diffuser wall. These findings lead to the following conclusion:

2. Thesis

Blowout stability of V-shaped flames characterized by strong swirl in lean premixed prevaporized burners enhances by applying a subsequent diffuser on the burner lip, which substitutes the outer recirculation zone. In this case, the appearing boundary layer near its wall ensures the improvement of the blowout stability. [P4-P9]

The flow patterns, flame shapes, and related phenomena of swirling flows are well-documented in the literature by, e.g., Beér [7] and Syred [8, 9]. A straight, a bistable, and a V-shaped operation were distinguished during the present measurement series which also resulted in significant changes in the chemiluminescence emission of OH^* , CH^* , and $\text{C}_{2,516}^*$. However, their intensity ratio, e.g., shown in Fig. 6, showed a smooth behavior in the function of the air-to-fuel equivalence ratio.

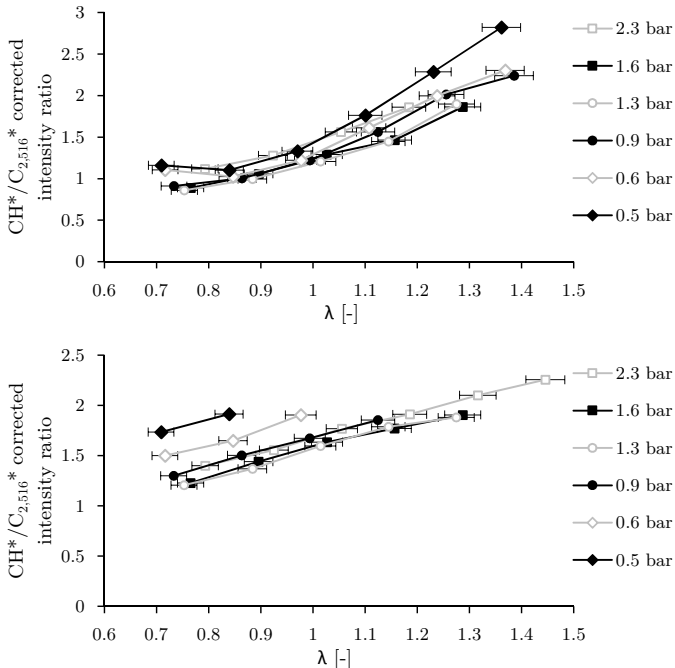


Figure 6: Corrected chemiluminescence intensity ratios of $\text{CH}^*/\text{C}_{2,516}^*$ of diesel oil (top) and rapeseed oil combustion (bottom).

Note that rapeseed oil combustion was sustainable in neither the bistable

nor the V-shaped regime unlike in the case of diesel oil combustion. Therefore, the number of measurement points increases with the atomizing pressure while it decreases the swirl number. Hence, the start of the mentioned regimes can be delayed, allowing stable operation at higher combustion air flow rates while the flame remains weakly swirling and straight. Based on these results, the following scientific contribution can be stated:

3. Thesis

In lean premixed prevaporized burners, OH^*/CH^* , $\text{OH}^*/\text{C}_{2,516}^*$, and $\text{CH}^*/\text{C}_{2,516}^*$ chemiluminescence intensity ratios do not show sudden changes in the function of the equivalence ratio. Even though the flame length, hence its shape, swiftly change due to the breakdown of the precessing vortex core. [P9, P10]

The $\text{A}^3\Pi_g\text{-X}^3\Pi_u$ transition of S(2,3) is responsible for the chemiluminescence emission of C_2^* [10], including the chemiluminescence peak at 554 nm. The $\text{C}_{2,554}^*$ was also observable in the case of diesel oil combustion, but not in the whole investigated range, and its intensity was relatively low. However, a more significant $\text{C}_{2,554}^*$ emission characterized rapeseed oil combustion, making this peak feasible for flame diagnostics, shown in Fig. 7.

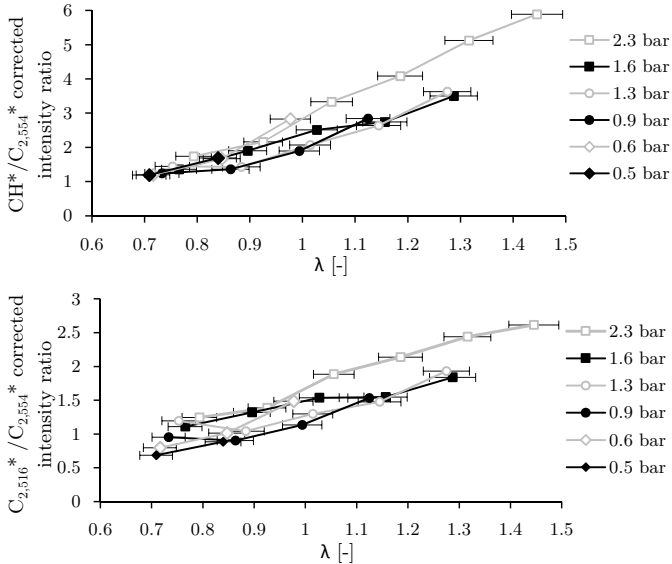


Figure 7: Corrected chemiluminescence intensity ratios of OH^* , CH^* , $\text{C}_{2,516}^*$ to $\text{C}_{2,554}^*$ of rapeseed oil combustion.

The most important properties of the trends are that they closely linear and monotonously increase in the function of air-to-fuel equivalence ratio. The number of measurement points at lower atomizing pressures is also limited due to the same reason as it was discussed earlier. By considering the newly identified emission peak and the corresponding intensity ratio characteristics, the scientific contribution can be summarized as:

4. Thesis

During the combustion of crude rapeseed oil under atmospheric conditions and in the investigated air-to-fuel equivalence ratio, $\lambda = 0.7 - 1.5$, a significant C_2^* chemiluminescence intensity peak was identified at 554 nm, $C_{2,554}^*$. Chemiluminescence intensity ratios of either OH^* , CH^* , or $C_{2,516}^*$ to $C_{2,554}^*$ increases monotonically with λ . [P9, P10]

4 Application of the results

Pneumatic atomization is widely used in many fields of engineering, including, e.g., medical, coating, painting, and agriculture technologies beside liquid fuel combustion. High atomization pressure results in a more homogeneous droplet distribution which can be important in all the mentioned applications. Therefore, estimating the average droplet size at elevated pressure conditions is highly relevant. Such measurements were unfeasible earlier while the Phase Doppler Anemometry did not allow the identification of droplets with few μm diameter. Nowadays, the lower limit of droplet detection is about 200 nm which was $\sim 20 \mu\text{m}$ in the 1980s.

Diffusers have already been applied for flame stabilization, especially in pulverized coal burners. However, a systematic analysis and its application in liquid fuel combustion bring a new potential to develop burners which are able to operate at even more lean conditions. It ensures lower NO_x emission besides marginal CO, unburnt hydrocarbon, and soot emission. This concept might receive more attention if the new emission standard enters in 2018 which halves the allowed NO_x and CO emission compared to the actual limitations.

Maneuvering capability of power plants becomes increasingly important as the number of wind and solar power plants grows continuously. While the emission standards have to be met even at partial loadings, an appropriate real-time combustion control based on the flame air-to-fuel equivalence ratio is required. A spectrometer is a suitable sensor for this purpose by following the mentioned measurement strategy. Consequently, the competitiveness of thermal power plants significantly increase.

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