Numerical and experimental studies of laminar counter-flow diffusion flames using biomass-based gaseous fuels

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Abstract
Further advance in the utilization of biomass-based gaseous fuels in internal combustion engines requires a deeper understanding of the complex combustion chemistry behind, as well as of the coupling of the chemistry with physical phenomena such as turbulence. The former is investigated in the present study combining both experiments with numerical simulations on different types of laminar diffusion flames (sooting and non-sooting).
Laser-based spectroscopy techniques, in particular laser-induced Rayleigh scattering and laser-induced fluorescence, are applied as diagnostic tools, which can provide accurate understanding of temperature distributions, as well as monitoring the flame front through the tracking of intermediate species, such as CH_2O, respectively. Additionally CH* chemiluminescence during the combustion is quantified, as this radical has considerable application in the reaction zone marking, providing a possibility to exactly measure the spatial position the flame.

Methods
The focus here is put on non-premixed product gas mixtures with CH_4 or CH_4 diluted by CO_2, N_2, CO, O_2, and/or H_2 as fuel and air as oxidizer at a wide range of air-fuel ratios. The flow velocities are increased until aerodynamic quenching of the flame occurs. The combustion behaviour at these different flame conditions is studied in a flat-flame counter-flow burner representing an essential element to advance the understanding of the so-called flamelet model of turbulent combustion processes. In correspondence to these experiments, the mentioned flames were numerically simulated by an implicit Fortran code capable of simulating this type of reactive flows [1].
By solving the governing equations for momentum, mass fractions, energy and total mass, temperature and species fraction profiles can be calculated for various strain rates, i.e., flow velocities, finally resulting in a flamelet library to be applied in future work for the numerical simulation of turbulent flames.
Furthermore, based on the simulated species profiles and the incorporation of the Rayleigh cross sections of the major species, together with the imaging system's

possible point spread function to minimize crosstalk background phenomena, a good fit between model and experiment can be established.
This study supports the study of Connelly et al. [2] that models should simulate experiments rather than experiment data being used to estimate quantities such as temperature indirectly (Figure 1).

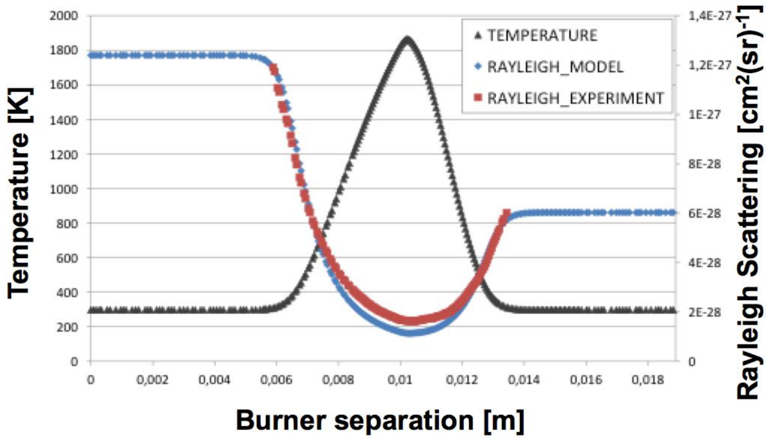

Figure 1. Numerical and experimental Rayleigh signals and temperature profile for non-premixed 40% CH_4 - 40% CO_2 -20% N_2 - air flames

Results

An increase of flow velocities and the thereby finally induced extinction, or straining out, of the diluted flames, are discussed with respect to the changes of the temperature profiles and decreasing peak temperatures both in regards to the corresponding Rayleigh signals as seen in Fig.2.

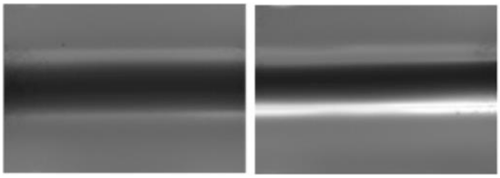

Figure 2. Experimental Rayleigh signal corresponding to temperature fields for diluted non-premixed 40% CH_4 - 60% CO_2 - air flames (top: air side; bottom: fuel side); left figure: $v_{air\,/\,fuel\ sides}$ = 20cms^{-1}, a= 41,1s^{-1}; right figure: $v_{air\,/fuel\ sides}$ = 60cms^{-1}, a= 123,1s^{-1}

Furthermore, with increasing strain rates a reduction of the flame width and flame shifts, as seen in Fig. 3, and additionally a rise of the CH_2O concentration as well

radicals in the pre-flame region like, e.g., CH_3O, are analysed. A major role plays the choice of the diluent, especially when trying make the flames more resistant to extinction by strain. Also an addition of O_2 to the fuel expanded the flammability of the system markedly with respect to strain.
Additionally the influences of N_2 shroud-flow velocities and diameters and resulting buoyancy effects due to a raise in temperature in the upper burner and a nozzle diameter of d < 25 mm are taken into account. [3]
The position of flames formed in a small burner (d = 24,7 mm) is greatly affected by buoyancy at low strains and increasing temperature, which induces a decrease of the density, at the top nozzle. This buoyancy effect decreases at higher velocities and hence higher strain rates.

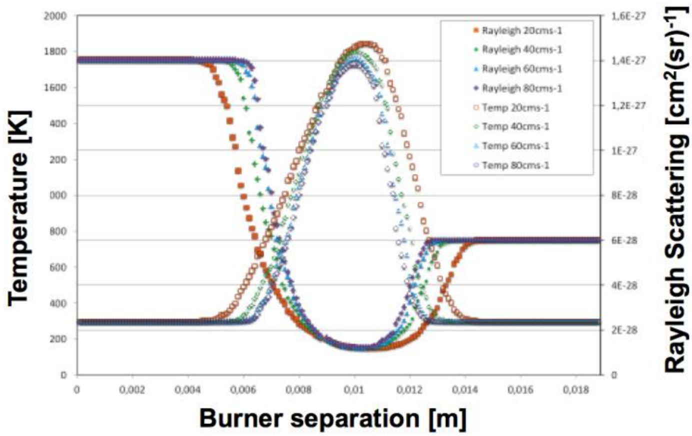

Figure 3. Numerical Rayleigh signals and temperature profiles for diluted non-premixed 40% CH_4 - 60% CO_2 - air flames (left: fuel-side, right: air-side) with increasing velocities on fuel and air sides and therefore strain rates

Conclusions

Due to the higher complexity of biomass-based gas fuels, in comparison to conventional fuels, regarding their composition and also higher heterogeneity depending on the conversion process, feedstock and gasifying agent a detailed characterization of their behaviour during combustion is still needed in order to improve the engine performance in an internal combustion engine, as well as control and reduce emissions.
Measurements of CH* chemiluminescence provide a possibility to advance the analysis of the spatial positions of the differing flames, unifying the evaluation of the reaction zones in both the experimental results and the numerical model. Especially soot precursors like CH_2O and temperature fields, in regards to the production of thermal NO, can therefore be thoroughly quantified.

References

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[2] Connelly, B.C., Bennett, B.A.V., Smooke, M.D., Long, M.B., A paradigm shift in the interactions of experiments and computations in combustion research, Proc. Comb. Inst. 32, 879-886 (2009).

[3] Oh, C., Ju Lee, E., Park, J., Effects of the burner diameter on the flame structure and extinction limit of counterflow non-premixed flames, international journal of spray and combustion dynamics (Volume 2, Number 3), 199-218 (2010)