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Towards a universal method for flame speeds determination

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Energy production from most renewable energy sources, such as wind, solar, and water (wave, tidal), is typically intermittent, thus energy storage is necessary. Chemical storage as one option is more economical in comparison to batteries. Energy carriers such as ammonia and methanol could be considered. The combustion of such energy vectors, which is the most effective way to use them as an energy source, is a key technology. Challenges, e.g. low flammability, heat release rate and emission, can be overcome by knowing the dynamics and chemistry of ammonia combustion.

Flame speed is a sizing metric of a fuel to be considered in designing energetic industrial systems such as IC engines and gas turbines. Indeed, this physicochemical property of a combustible mixture notably influences the heat release rate and flame stabilization. Moreover, its significance makes it a major target for the validation of kinetic mechanisms. For example, the flame speed of ammonia or ethanol is around one fourth compared to traditional hydrocarbon fuels. Flame stabilization difficulties, possibly encountered in industrial systems, can be solved by technical adjustments (i.e. air preheating, compression ratio increase, oxygen-enriched air, co-firing with methane or syngas).

The accuracy of experimental flame speed determination (target data for numerical schemes) for slow flames is the main issue to be addressed here.

The ultimate goal is to characterize the reactivity of slow flames over a wide range of unexplored pressure and temperature conditions (p > 1 MPa & T > 500 K) with the following objectives:

- Ob1 Evaluate radiation effects for weakly reactive fuels using two complementary setups.
- Ob2 Evaluate buoyancy effects on the determination of flame speed for low reactivity mixtures.
- Ob3 Propose semi-physical models to subsequently correct all data available in the literature for slow flames and evaluate potential applicability for fuels with comparable combustion physics (e.g. refrigerants).

The research group composed of ITV (RWTH Aachen University) and ICARE (CNRS University of Orléans) have developed experimental facilities to tackle these scientific objectives.

Flame speed measurements under microgravity conditions will be performed both in the Bremen drop tower facility and in the airplane. The drop tower is operated by ZARM, the Center of Applied Space Technology and Microgravity of the University Bremen.

The main objective of this study is to investigate the reactivity of flames strongly influenced by buoyancy under earth gravitational conditions (1 g), which can be obtained by varying the oxygen content in the oxidizer mixture and approaching the fuel-rich flammability limit. The gravitational force can lead to a deformation of the initially spherical flame shape, making the determination of laminar flame speed, a fundamental metric of a combustible mixture, quite challenging. The upward motion of buoyant flames induces a complex flow resulting in flames with mushroom-like shapes. Therefore, the validity of the existing flame speed extraction techniques for slowly propagating flames is unclear. Consequently, the accuracy of the experimental data obtained under normal gravity should be addressed. By suppressing the effect of buoyant flame motion under microgravity (µg), laminar flame speeds can be extracted accurately. The comparison of flame speed data obtained with and without gravitational forces will lead to the development of novel post-processing routines for buoyant flames. To achieve this goal, experiments were conducted during a collaborative campaign between RWTH Aachen University, Germany, and ICARE, France, using two fuels: (i) ethanol as a representative of a typical high-temperature branch reacting fuel, (ii) and diethoxymethane being a bio-hybrid fuel and for its multistage ignition behavior.

Preliminary Results

Experiments were conducted in a pressure-release-type dual chamber, which is adequate for aircraft-related safety requirements. A conventional shadowgraphy system is used to visualize the flame morphology, as can be seen in Fig. 1(left). After spark ignition, the flame propagates spherically under microgravity conditions, whereas it is highly deformed under terrestrial gravity (cf. Fig. 1(right)). Due to the density difference between the burned and unburned gas, these slowly propagating flames develop an upward motion, and the initially spherical flame deforms and attains a mushroom-like shape. The upward motion of buoyant flames induces a complex flow. In contrast to ideally spherical flames, different points of the flame front propagate with a different absolute speed, making the extraction of laminar flame speed extremely difficult. The methods found in the literature to assess buoyant flames differ quite significantly between studies and seem somehow arbitrarily chosen, as recently demonstrated by Berger et al. [1].

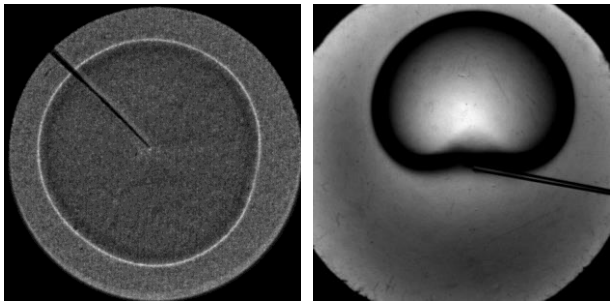

Figure 1: *Exemplary images of fuel-rich ethanol flame under µg (left) and highly buoyant at the same conditions under terrestrial gravity. (ϕ = 1.4, T_0 = 373 K, P_0 = 3 bar, oxidizer: 12% O_2 - 88% N_2 in volume).*

To determine the flame radius R from the raw images recorded by the high-speed camera, the surface of the spherical flame is projected, and the instantaneous flame front radius can be deduced. The evolution of flame propagation speed as a function of flame stretch for ethanol flames at various equivalence ratios is shown in Fig. 2. By increasing the equivalence ratio, the burned-gas Markstein length $\mathcal{L}_b$, which represents the sensitivity of flame speed to stretch, decreases significantly. Considering these low flame speeds, radiation effects are of major concern as previously highlighted by ITV and should be considered, as it was shown in the previous study of Hesse et al. [2]. Further work should be done to optimize the analytical model.

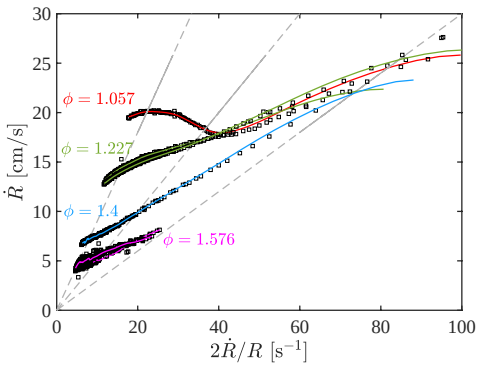

Figure 2: *Evolution of burned-gas flame speed as a function of flame stretch for ethanol flames at various equivalence ratios. (T_0 = 373 K, P_0 = 5 bar, oxidizer: 12% O_2 - 88% N_2 in volume).*

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