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A comparative study of the effect of varied reaction environments on a swirl stabilized flame geometry via optical measurements

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ABSTRACT

The present work is a part of a larger experimental campaign which examines the behaviour of various fuels on a swirl stabilized flame burner configuration. Overall, detailed speciation measurements and temperature measurements were combined with optical measurements. The work presented here concerns the part of the experimental campaign which deals with the optical characteristics of the examined flames. The work adds to the growing database of experimental measurements assessing engine-relevant reaction environments which shift from traditional ones in order to meet pollutant emission regulations and efficiency standards. Here, the oxidation of several commonly used fuel and fuel surrogates that are subjected to the addition of a bio-derived fuel additive (dimethyl ether) and emulated exhaust gas recirculation (EGR) is studied in a laboratory-scale swirl stabilized burner. The natural flame chemiluminescence has been exploited to selectively measure line of sight CH∗ and OH∗ profiles for combinations of these fuels and reaction environments. As a result, the geometry and intensity of the reaction and oxidation zones have been parametrically evaluated for a sizable number of initial conditions. From an analysis of the collected data, a chemical uniqueness in methane and propane flames has been found along with a change in flame topology as a function reactant temperature and dilution with inert gases, while the flames were virtually unaffected by all other variations in reaction conditions. This insensitivity provides confidence in the use of tailored in-cylinder fluid dynamic/chemical interactions to extend engine operating conditions to otherwise difficult regimes.

1. Introduction

The Paris Agreement has set ambitious targets for the worldwide reduction of toxic and greenhouse chemical emissions into the atmosphere [1]. Consecutively, engine manufacturers are facing legislative constrains which are expected to tighten the already stringent pollutant limits for future engines. In recent years, these perpetually expanding regulations, along with concerns over fossil fuels scarcity, have led to a large aggregate of research concerning the extrapolation of conventional combustion strategies that have been used in engines and combustors to more clean, efficient, and fuel flexible regimes [2]. This research has led to several techniques which have been largely adapted nowadays by commercially available internal combustion engines (ICEs), such as, exhaust gas recirculation [3], down-size and boost [2], and bio-derived fuel additives [4]. Other, more long-term solutions have also been suggested, which promise even more significant improvements in engine efficiency and fuel flexibility and emission performance [5]. These advanced engine regimes [6–8] typically employ a more chemical kinetically controlled combustion strategy at lower temperature and leaner conditions than conventional ICEs. Unfortunately, combustion control throughout the engine operating map and low reaction propagation stabilities at these fuel lean operating regimes may occur [5]. Efforts to reassure the effectiveness of the aforementioned techniques as well as to mitigate challenges with longer term solutions has spawned a plethora of research trying to understanding the tightly coupled fluid dynamic and fuel chemistry

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interactions [8–9]. Several studies have focused on studying these interactions directly in engines [10,11], but conventional diagnostics used in apparatuses with no optical or physical in-situ in cylinder access have been proved challenging [12,13], and although in some cases, the arduous task of mounting ample diagnostics to laboratory engine rigs has proved successful [14], the ability to extrapolate these results to other combustion platforms is a straight forward process. On the other hand, the use of comprehensive laser-based diagnostics does not unravel entirely all difficulties since the compromise for achieving the optical access is the difficulty to achieve otherwise trivial in-cylinder conditions to such as compression ratios and the accompanied heat losses [15]. As a result, researchers try to combine a variety of analytical and optical methodologies in similar or based on previous results on similar test rigs to acquire the maximum synergy and describe to the best possible degree a given engine behavior [16]. To generalize experimental findings, fuel oxidation experiments can be conducted in well-characterized, laboratory-scale reactors as a function of physical state parameters [17,18]. Typically, data regarding the reacting flow is then utilized as validation targets for fundamental fluid dynamic and chemical models, which collectively act as simulation tools for the more complex cases. Unfortunately, these transport models for typical in-cylinder environments quickly become heavily restrained by the available computational capabilities. While a large body of work has focused on measurements tied to specific combustors as well as the development of fundamental physics models, there is a limited amount of informatic data [e.g. 19, 20] for the generic reactive in-cylinder flow environments. On the other hand, swirl burners have been commonly used in a variety of combustion applications, ranging from utility boilers and gas turbines to coal combustors. These also represent convenient laboratory scale test beds, for the direct application of a range of experimental techniques in the study of the combined effects of flame stabilization, mixture dilution, inlet conditions and emission performance for the development of a wide variety of technical combustion systems [21–23]. More specifically, in recent experimental work [24], stereoscopic particle induced velocimetry (SPIV), together with Planar induced fluorescence of OH radicals, and chemiluminescence have been used in order to depict flow fields and to capture reaction zones and flame stabilization regions. The effect of dilution with CO_2 and H_2O in methane and DME flames on NO formation has, also, been examined along with mathematical modeling [25], and correlations of the chemical effect of dilution on emissions have been discussed on the basis of the local chemistry and its interaction with the inlet conditions. The effects of CO_2 addition have been studied in [26] through chemical analysis of the participating radicals and reactions, over a range of flame conditions.

This study presents the first in a campaign by the current author list to examine the behaviour of various fuels on the given setup under conditions frequently met in practical applications. Overall, detailed speciation measurements and temperature measurements were combined with optical measurements and the work presented here concerns the part of the experimental campaign which deals with the optical characteristics of the examined flames. The study on the one hand adds to the database of immediately useful fuel oxidation data for a generic commercial combustor and on the other hand serves as a means of evaluating operating parameters such as dilution, preheating and fuel interchange in engine related conditions. More specifically, the study is facilitated by flame chemistry measurements of a wide variety of fuels that are used as fuels or fuel surrogates in automotive, marine and aviation transportation engines along with bio-derived fuel dopants and added diluent gases that represent the exhaust gas recirculation cycles of an operating engine. Furthermore, the burner has been configured to generate a swirling flow at the nozzle exit to emulate a swirl flame-stabilization technique that has been proposed for engines running in a lean operation mode [27]. While the current laboratory burner does not exactly reproduce the reactive in-cylinder environment of an ICE, it offers effortless optical access and control, and therefore a straightforward coupling of standard analytical chemistry instruments to the rig in order to probe the chemical characteristics of the reacting flow. Nonetheless, there are significant differences in flame formation, confinement, hence pressure conditions which need to be seriously taken into account when comparing the findings of the present work with engine studies. In the current study, the line of sight natural luminosity of the flame has been measured simultaneously for selective OH∗ and CH∗ chemiluminescence emission bands, which can be considered good markers to monitor heat release oscillations and heat release rates as mentioned in [28–29] However, effects of the turbulence intensity, strain rate, flame front curvature, mixture composition, temperature and pressure and fuel type need to be included to obtain quantitative heat release rate correlations [28–35]. The obtained images are then deconvolved into constructs that define the geometry of the reactive and oxidative flame zones, where changes to the flame structure are then correlated to changes in the operating conditions. These data may potentially be used to understand the effect that unconventional utilized fuel blends and varying operation parameters could have on flame characteristics.

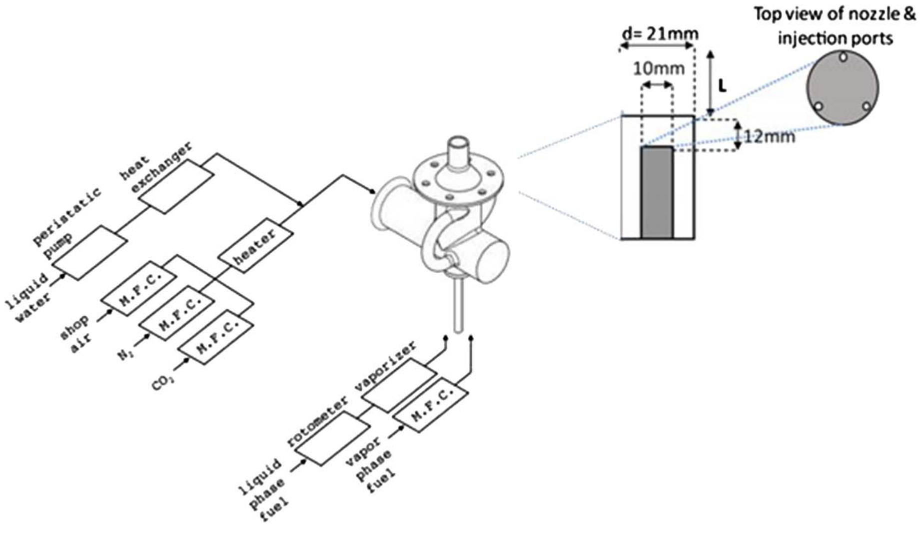

Fig. 1. An illustration of the air, fuel and diluent plumbing and control system of the NTUA swirl burner.