



Characteristics of turbulent *n*-heptane jet flames in a hot and diluted coflow



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ABSTRACT

Distinctive behaviour of turbulent *n*-heptane jet flames is revealed by conventional photography and laser-induced fluorescence of the hydroxyl radical (OH-LIF) performed in a Jet in Hot Coflow (JHC) burner. Prevaporised *n*-heptane, carried by air, issues into a hot vitiated coflow at two temperatures (1250 K and 1315 K) with three coflow oxygen levels ($X_{O_2} = 3\%$, 6%, and 9%), mimicking moderate or intense low oxygen dilution (MILD) combustion conditions. Results for *n*-heptane flames are compared to those for ethylene, ethanol, and natural gas flames. Two main discrepancies are revealed: firstly, the apparent liftoff height of *n*-heptane flames decreases gradually with the increasing coflow oxygen level, while the apparent liftoff height of other fuels exhibit a non-monotonic trend; secondly, a transitional flame structure of *n*-heptane occurs in a coflow with $X_{O_2} = 3\%$, while this structure occurs in a coflow with $X_{O_2} \geq 9\%$ for other fuels. Calculations using a closed homogeneous reactor model support the interpretation of the experimental data, namely that the temporal profiles of OH in the *n*-heptane flames are similar for the 3% and 9% O_2 cases, differing from the behaviour of other fuels. A comparative analysis of *n*-heptane and ethanol chemistry, focused on the fuel pyrolysis and net negative heat release regions, suggests that it is more difficult for *n*-heptane than ethanol to meet one of the criteria of MILD combustion.

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1. Introduction

Moderate or Intense Low-oxygen Dilution (MILD) combustion has attracted extensive research interest [1–12], driven by a long-term goal to provide energy in a more efficient and sustainable way. MILD combustion occurs in a hot and diluted environment, typically achieved by strong preheating and dilution of reactants using hot exhaust gases.

The enhanced recirculation or entrainment of hot exhaust gases under MILD combustion conditions can be achieved through various means, such as a reverse-flow design [13] or with the use of high momentum fuel jets [14]. In these configurations, the characteristic timescale of the fluid flow is intentionally shortened [6]. More importantly, the enhanced recirculation dilutes the fresh reactants and reduces the local oxygen concentration, thereby increasing the chemical timescale. The combined effects of short fluid timescale and long chemical timescale lead to a strong interaction between turbulence and chemistry under MILD combustion conditions [15,16]. This dominant turbulence-chemistry interaction further complicates the already complex

combustion processes, hence it is essential to isolate different parameters through carefully designed experiments in order to enable a deeper understanding of the effect of these parameters on the combustion process. One method of separating these parameters is through the use of a laboratory-scale Jet in Hot Coflow (JHC) burner [17], which consists of a cold jet issuing into a hot and vitiated coflow, emulating MILD combustion conditions. This configuration provides control over the boundary conditions and allows optical access for *in situ* measurements.

A large body of research work has been conducted to improve the understanding of the flame stabilisation mechanisms and the resultant characteristics in MILD combustion [7,8,10,15,16,18–25]. The vast majority of these studies were focused on simple gaseous fuels, such as hydrogen and methane. For instance, Dally et al. [16] reported the necessity of a high scalar dissipation rate in the vicinity of the jet exit plane in order to prevent early ignition of methane, caused by flame propagation from downstream, before the fresh mixture is well diluted by hot exhaust gases. This finding agrees with a study by Katsuki and Hasegawa [15], who found that a rapid dilution of reactants via a shearing motion with high speed air was required to ensure reactions proceed under highly vitiated conditions. Nevertheless, it is worth noting that laminar MILD flames of various methane- and ethylene-based fuels

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have also been established under low-strain conditions in many experimental configurations consisting of a jet issuing into a hot and diluted coflow [26,27].

Minamoto and Swaminathan [24] investigated the often-cited “homogeneous” characteristic of MILD combustion in a three-dimensional direct numerical simulation (DNS) study of methane flames in a near-uniform mixture-fraction-field, with variations of approximately $\pm 5\%$ of the mean value. Thin regions of intense reactions were revealed by their analysis, which indicated the existence of flamelets [24]. These flamelets interacted with each other frequently in space and time, leading to the thickening of the reaction zone and the appearance of non-flamelet behaviour [24,28]. This is consistent with an experimental study on MILD methane flames by Sidey and Mastorakos [25], where thin flame fronts were revealed by instantaneous imaging of OH.

Previous numerical studies of methane by de Joannon et al. [29–31] demonstrated that the MILD combustion regime is associated with several common signatures in the heat production rate profile: the broadening of the heat production profile with a single peak in mixture fraction space, the lack of correlation between the location of the peak heat production rate (Z_{hmax}) and the stoichiometric mixture fraction, and the absence of a net negative heat release region. The absence of a net negative heat release region is attributed to the suppression of pyrolytic reactions, which is also responsible for low soot formation, an important feature of MILD combustion [9].

Compared to studies of methane-based flames, published results are sparse on more complex fuels, such as oxygenated fuels and long-chain alkanes. Although previous work has indicated that MILD combustion is insensitive to fuel type when simple hydrocarbons are mixed with hydrogen [32], the role of fuel structure on the flame stabilisation mechanism and the typical MILD combustion characteristics should not be underestimated. For instance, Oldenhof et al. [33] investigated the ignition event and liftoff behaviour of various jet-in-hot-coflow flames via high-speed imaging. They found that the addition of higher alkanes, such as ethane and propane, to methane flames significantly affects the chemical timescale, thus the liftoff height [33]. Another study on a reverse-flow MILD combustor [13] reported that the combustion stability was strongly dependent on the fuel type: unstable combustion of *n*-heptane was observed at higher equivalence ratios under elevated pressures, meanwhile MILD combustion of ethanol with invisible flame and low emissions were established under the same conditions. Identifying the reasons for the difference in stability between the two flames was not possible because of limited control over the mixing process inside the combustor. Reddy et al. [34] studied combustion of biodiesel and biodiesel blended with standard diesel in a two-stage combustor under MILD combustion conditions. Lower emissions of NO_x and unburned hydrocarbons (UHCs) were produced from biodiesel blended with standard diesel than pure biodiesel. This was thought to be caused by a faster evaporation of standard diesel due to its lower viscosity and boiling point [34], further highlighting the potential sensitivity of MILD combustion to the fuel type.

The impact of fuel type has also been investigated for solid fuels in the furnace environment. Saha et al. [7] investigated MILD combustion of pulverised brown and black coal in a self-recuperative furnace: NO_x emissions from black coal were measured to be much higher than those from brown coal combustion, which was explained by a higher nitrogen content in black coal [7]. Weber et al. [18] compared the combustion performance of various fuels in a furnace, including natural gas, light fuel oil (LFO), heavy fuel oil (HFO), and coal. When natural gas and LFO were burnt, the whole furnace was illuminated while no visible flame was observed [18]. In contrast, visible flames with high NO_x emissions were always observed when HFO and coal were fired instead,

though NO_x emissions were still lower than those generated in the normal air-fuel combustion in the same furnace [18]. Hence they pointed out that even though exhaust gas recirculation is not effective in reducing NO_x formation via the fuel-NO mechanism, it helps reduce NO_x through the enhanced NO reburning mechanism by providing locally sub-stoichiometric conditions [18].

A limited number of experimental studies [35–37] on the flame structure of complex fuels have been performed in a well-controlled environment, where operating parameters can be controlled and changed independently. Rodrigues et al. [35] investigated ethanol flame structure in both a hot diluted coflow and air. They found that the mixing with a hot diluted coflow, along with an enhanced evaporation of droplets, provided a richer gaseous mixture towards the spray axis and reduced the peak flame temperature [35]. They also investigated the effects of coflow temperature and dilution level, though the two parameters were not varied independently [36]. It was found that the coflow temperature and composition had little impact on the droplet mean size and velocity distribution. However, they affected the flame liftoff heights by changing the droplet vaporisation timescale and the chemical timescale [36]. O’Loughlin et al. [37] performed planar imaging of OH and CH_2O of methanol spray flames in a hot and diluted coflow to understand the auto-ignition process. Similar to gaseous fuels, CH_2O was detected upstream of OH, reinforcing its important role as an ignition precursor [37]. Different from gaseous fuels, a double-flame-front was commonly found in methanol flames, which may be formed by local ignitable mixtures due to droplet evaporation [37].

Previous work [7,13,18,34] has shown that complex fuels burning under MILD combustion conditions exhibit distinct features to simpler fuels, such as hydrogen and methane. These features include higher pollutant emissions [7,18,34], the existence of visible flames [13,18], and combustion instabilities [13]. Part of the dissimilarities were ascribed to different physical properties of the fuels, however, because most of the previous work was not conducted in a well-controlled environment, the understanding of the underlying fundamentals is limited. In particular, prominent combustion instabilities reported for *n*-heptane flames in a pressurised MILD combustor [13] are not well understood. In order to provide more insights to the different behaviour of *n*-heptane flames, the present study is focused on pre-vaporised *n*-heptane to investigate the chemical effects. Moreover, results for *n*-heptane are directly compared to those for natural gas, ethylene, and ethanol to demonstrate the distinctive characteristics of *n*-heptane. It is worth mentioning that *n*-heptane is of interest to a wide combustion community as it is a primary reference fuel for octane rating and is widely used as a surrogate fuel for diesel fuel in studies [38–40]. Experiments in the present study are conducted in a JHC burner as it provides a well-defined environment, emulating MILD combustion conditions. Visualisation of *n*-heptane flames is performed with conventional photography and laser-induced fluorescence of OH (OH-LIF) to reveal the flame structure, and an in-depth chemical analysis is performed to assist the explanation of the observed flame characteristics.

2. Experimental details

2.1. Experimental setup and operating conditions

Presented in Fig. 1 is the experimental setup of the current study, which is the same as a previous study [41]. A controlled evaporator and mixer (CEM) is used to preheat and premix *n*-heptane with carrier air. The temperature of the heater inside the CEM was set to 473 K by a control unit, which is higher than the boiling temperature ($T_{boil} = 371$ K) of *n*-heptane. The pipeline

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