Auto-ignition and flame stabilization of hydrogen/natural gas/nitrogen jets in a vitiated cross-flow at elevated pressure

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ABSTRACT

The influence of natural gas (NG) on the auto-ignition behavior of hydrogen (H_2)/nitrogen (N_2) fuel jets injected into a vitiated cross-flow was studied at conditions relevant for practical combustion systems ($p = 15$ bar, $T_{cross-flow} = 1173$ K). In addition, the flame stabilization process following auto-ignition was investigated by means of high-speed luminosity and shadowgraph imaging. The experiments were carried out in an optically accessible jet in cross-flow (JICF) test section. In a H_2/NG/N_2 fuel mixture, the fraction of H_2 was stepwise increased while keeping the N_2 fraction approximately constant. Two different jet penetration depths, represented by two N_2 fraction levels, were investigated. The results reveal that auto-ignition kernels occurred even for the lowest tested H_2 fuel fraction ($X_{H_2/NG} = X_{H_2}/(X_{H_2} + X_{NG}) = 80\%$), but did not initiate a stable flame in the duct. Increasing $X_{H_2/NG}$ decreased the distance between the initial position of the auto-ignition kernels and the fuel injector, finally leading to flame stabilization. The H_2 fraction for which flame stabilization was initiated depended on jet penetration; flame stabilization occurred at lower H_2 fractions for the higher jet penetration depth ($X_{H_2/NG} = 91\%$ compared to 96%), revealing the influence of different flow fields and mixing characteristics on the flame stabilization process. It is hypothesized that the flame stabilization process is related to kernels extending over the duct height and thus altering the upstream conditions due to considerable heat release. This enabled subsequent kernels to occur close to the fuel injector until they could finally stabilize in the recirculation zone of the jet lee.

1. Introduction

Utilization of hydrogen (H_2)-rich fuels in modern combustion devices is becoming increasingly relevant due to the need to reduce CO_2 emissions and the demand for alternative energy sources. Hydrogen is a highly reactive molecule with considerably different combustion properties compared to common fuels, such as natural gas (NG). One important characteristic is its high propensity to auto-ignite, which requires careful consideration when designing fuel-flexible low-NO_x

Nomenclature

Symbols

B	vertical blockage ratio
J	jet to crossflow momentum flux ratio
L	distance to the fuel injector
p	pressure
T	temperature
u	velocity
X	mole fraction
$X_{H_2/NG}$	mole ratio of H_2 of the reactive species H_2 and NG in the jet: $X_{H_2}/(X_{H_2} + X_{NG})$

$X_{N_2,high}$	test case with higher N_2-dilution and jet penetration
$X_{N_2,low}$	test case with lower N_2-dilution and jet penetration
Φ	equivalence ratio

Acronyms

FI	fuel injector
JICF	jet in cross-flow
NG	natural gas

combustion technologies such as lean premixed combustion (LPC) systems in stationary gas turbines [1] or H_2-fueled internal combustion engines [2]. Unwanted auto-ignition can lead to severe combustor damage and its avoidance requires detailed understanding of auto-ignition characteristics of H_2-containing fuel blends.

Auto-ignition chemistry is strongly influenced by fuel and oxidizer composition, along with temperature, pressure, and stoichiometry. Typical H_2-rich fuels are syngases derived from the gasification of coal or biomass. Besides inert components like N_2 or carbon dioxide (CO_2), these syngases contain H_2, carbon monoxide (CO) and small amounts of hydrocarbons, predominantly methane (CH_4). While CO was found to significantly influence H_2 auto-ignition chemistry only for relatively high fractions of CO (above 50 vol. %) [3–6], the behavior of H_2/CH_4 systems is more complex. The influence of the H_2/CH_4-ratio on ignition was reported to depend on the temperature and pressure boundary conditions [7–9]. Thiessen et al. [9] modeled the ignition behavior of H_2/CH_4 mixtures for H_2 fractions of 0–100% over a wide range of conditions ($T = 800$–1500 K, $p = 1$–100 bar). At lower temperatures, they found that minor fractions of H_2 in CH_4 strongly promote ignition due to enhanced radical production accelerating the rate of methane oxidation. In this temperature range, higher H_2 fractions do not have any further promoting effects. At higher temperatures, where H_2 reactions are dominated by chain-branching reactions, even small fractions of CH_4 act as an ignition inhibitor, since radicals are consumed by CH_4 reactions. The transition between these ranges is pressure dependent. These findings might explain the partially different trends reported in literature. For example, Fotache et al. [10] studied ignition of CH_4 enriched with H_2 in heated air in a non-premixed counterflow flame for pressures between 0.2 and 8 atm. They reported that small amounts of H_2 significantly promoted CH_4 ignition, but that the effect decreased with increasing H_2 fraction, and that fractions exceeding 30% did not have any further promoting effect. In contrast, a shocktube study ($T = 1132$–1553 K, $p \approx 18$–25 atm) of Petersen et al. [11] showed that ignition was more facilitated for the higher tested H_2 fraction: 20% H_2 in CH_4 reduced the ignition delay by a factor of 3, whereas 40% H_2 reduced it by nearly a factor of 10 compared to pure CH_4. This trend is in line with an empirical relation suggested by Cheng and Oppenheim [12] derived from a shocktube study of H_2 in CH_4 varying from 0 to 100%. Other shocktube studies over such a wide H_2/CH_4-range reported that for H_2 fractions exceeding 80%, ignition is dominated by the H_2 chemistry, exhibiting its complex pressure dependence [13–15]. Nevertheless, both a numerical investigation of Ju and Niioka ($T = 1200$–1400 K, atmospheric pressure) and a study of Chaumeix et al. ($T = 1250$–2000 K, $p = 1.5$–16 bar) showed that even the addition of small amounts of CH_4 to H_2, i.e. less than 15%, drastically decreased the propensity to auto-ignite [16,17].

The majority of the above mentioned studies were conducted at homogeneous conditions in order to investigate chemical characteristics of auto-ignition. In technical applications, however, auto-ignition is a highly complex process involving turbulent mixing and fluid dynamics, in addition to normal auto-ignition chemistry [18].

The present study aims at investigating the auto-ignition behavior of H_2/N_2 mixtures in the presence of minor amounts of NG, which mainly consists of CH_4, at conditions relevant for technical systems. For this reason, the investigations were carried out in a jet in cross-flow (JICF) configuration. JICFs exhibit highly strained regions of non-uniform mixing, reaction rate, and temperature, and therefore mimic conditions of technical relevance [19–21]. In addition to the auto-ignition onset, kernel propagation and the subsequent flame stabilization process was studied using high-speed luminosity and shadowgraph imaging. The chosen operating conditions, namely elevated pressure (15 bar), high cross-flow temperature (1173 K) and velocity (200 m/s), along with $H_2/NG/N_2$ fuel jets being injected into vitiated air, are in the range which is relevant for mixing sections of gas turbine reheat combustors [1,22–24]. The current work complements recent auto-ignition studies of various H_2/N_2 fuel mixtures [1,25] in order to provide a better understanding of
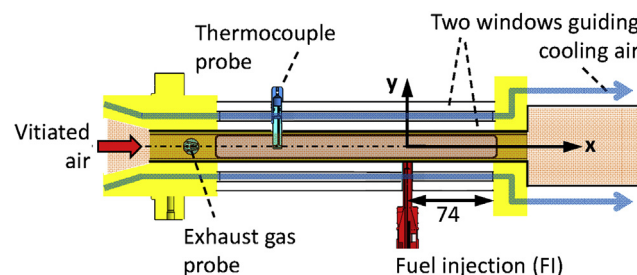

Fig. 1 − JICF test section.