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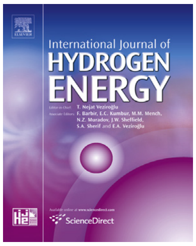

Large eddy simulation of highly turbulent under-expanded hydrogen and methane jets for gaseous-fuelled internal combustion engines

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ABSTRACT

Burning hydrogen in conventional internal combustion (IC) engines is associated with zero carbon-based tailpipe exhaust emissions. In order to obtain high volumetric efficiency and eliminate abnormal combustion modes such as preignition and backfire, in-cylinder direct injection (DI) of hydrogen is considered preferable for a future generation of hydrogen IC engines. However, hydrogen's low density requires high injection pressures for fast hydrogen penetration and sufficient in-cylinder mixing. Such pressures lead to chocked flow conditions during the injection process which result in the formation of turbulent under-expanded hydrogen jets. In this context, fundamental understanding of the under-expansion process and turbulent mixing just after the nozzle exit is necessary for the successful design of an efficient hydrogen injection system and associated injection strategies. The current study used large eddy simulation (LES) to investigate the characteristics of hydrogen under-expanded jets with different nozzle pressure ratios (NPR), namely 8.5, 10, 30 and 70. A test case of methane injection with NPR = 8.5 was also simulated for direct comparison with the hydrogen jetting under the same NPR. The near-nozzle shock structure, the geometry of the *Mach* disk and reflected shock angle, as well as the turbulent shear layer were all captured in very good agreement with data available in the literature. Direct comparison between hydrogen and methane fuelling showed that the ratio of the specific heats had a noticeable effect on the near-nozzle shock structure and dimensions of the *Mach* disk. It was observed that with methane, mixing did not occur before the *Mach* disk, whereas with hydrogen high levels of momentum exchange and mixing appeared at the boundary of the intercepting shock. This was believed to be the effect of the high turbulence fluctuations at the nozzle exit of the hydrogen jet which triggered *Gortler* vortices. Generally, the primary mixing was observed to occur after the location of the *Mach* disk and particularly close to the jet boundaries where large-scale turbulence played a dominant role. It was also found that NPR had significant effect on the mixture's local fuel richness. Finally, it was noted that applying higher injection pressure did not essentially increase the penetration length of the hydrogen jets and that there could be an optimum NPR that would introduce more enhanced mixing whilst

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delivering sufficient fuel in less time. Such an optimum NPR could be in the region of 100 based on the geometry and observations of the current study.

Introduction

Hydrogen-fuelled internal combustion engines

In order to tackle issues related to the ever increasing cost of conventional fuels and carbon emissions, it is necessary to diversify towards cleaner and more sustainable fuels. Accordingly, several liquids and gases have been proposed as alternative fuels for internal combustion (IC) engines; among them, gaseous hydrogen (H_2) can offer a promising long-term solution. The concept of a hydrogen economy has been proposed since the mid-1970s [1,2]. Several experimental and computational studies have been conducted on the development of hydrogen-fuelled IC engines in the past 15 years [3–22]. Port fuel injection (PFI) [6–12] and in-cylinder direct injection (DI) [13–22] of hydrogen are the two typical options for hydrogen-fuelled IC engines. DI offers higher volumetric efficiency and eliminates abnormal combustion modes such as pre-ignition and backfire. These attributes, in conjunction with the flexibility in possible injection strategies, make DI preferable for hydrogen IC engines. However, hydrogen's low density requires high injection pressures in order to achieve fast fuel delivery and optimise mixture formation. Such pressures lead to turbulent under-expanded hydrogen jets past the nozzle exit [18,22]. Therefore, fundamental understanding of the under-expansion process and turbulent mixing just after the nozzle exit is necessary for the design of an efficient hydrogen injection system and associated injection strategies for enhanced engine performance.

Under-expanded jets

Definition

The ratio of the nozzle total pressure (P_0) to the ambient (in-cylinder) static pressure (P_∞), namely the nozzle pressure ratio (NPR), has a significant effect on the characteristics of a gaseous jet issuing from a circular nozzle. Based on the level of NPR, jets can be classified as subsonic, moderately under-expanded and highly under-expanded [23–25]. Specifically, Donaldson and Snedeker [25] categorized the gaseous jets into three major types based on the NPR (P_0/P_∞) and under-expansion ratio (P_1/P_∞) as subsonic ($1 > P_\infty/P_0 > 0.528$, $P_1/P_\infty = 1$), moderately under-expanded ($0.48 > P_\infty/P_0 \geq 0.26$, $1.1 < P_1/P_\infty \leq 2$) and highly under-expanded ($0.26 \geq P_\infty/P_0 \geq 0$, $2 \leq P_1/P_\infty \leq \infty$). For NPR above ~4 the jet is considered to be highly under-expanded. As illustrated in Fig. 1, at such condition, infinite number of *Mach* waves, namely the *Prandtl–Meyer* expansion fan, form at the nozzle lip that spread out to the jet boundary and reflect as weak compression waves which form the intercepting oblique shock that is ended by a slightly curved strong normal shock so-called *Mach* disk [23]. The intercepting shock and the *Mach* disk form the first shock cell that is labelled "barrel shape shock" since it has a cylindrical shape. On a 2-D plane a reflected shock and a slip line is seen at the "triple point" which is the merging location of the intercepting shock and the *Mach* disk (see Fig. 1). The flow behind the *Mach* disk is subsonic, whilst the flow behind the reflected shock is still supersonic [23–25]. For higher degrees of under-expansion, *e.g.* NPR ≈ 8, the subsonic core behind the *Mach* disk rapidly accelerates and becomes supersonic once more, which then shapes a second shock cell that may resemble the first shock cell and even include a normal shock comparable to the *Mach* disk [25]. At extremely high levels of NPR, a very large *Mach* disk forms at the nozzle exit, with no additional normal shocks downstream, and the jet then decays resembling a subsonic jet [25].

Near-nozzle sonic characteristics

The near-nozzle sonic characteristics of under-expanded jets are quantified by several important parameters that include the dimensions of the *Mach* disk, angle of the reflected shock at the triple point and length of the shear layer thickness (maximum distance between the slip line and the reflected shock). These, not only provide important information regarding the upstream condition and effective injection pressure, but also have significant effect on the annular shear layer thickness and consequently on the mixing characteristics of the under-expanded jet. These parameters can also be used as fundamental measures for comparing under-expanded jets with different values of NPR and also for validating numerical models of these types of jets.

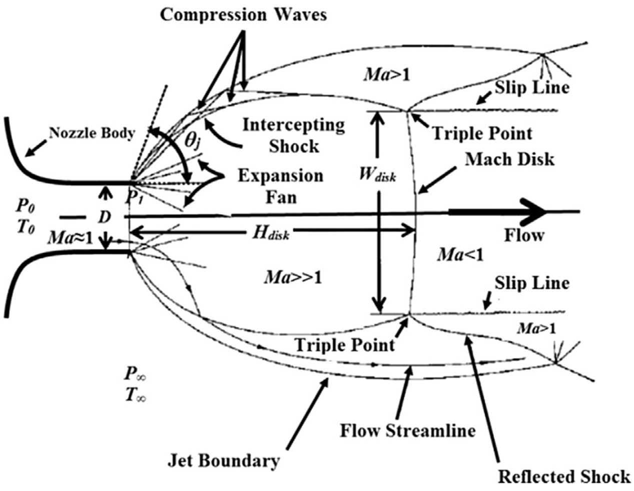

Fig. 1 – Schematic of the near-nozzle structure of under-expanded jets (based on Crist et al. [23]).