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## Gas dynamics and flow characteristics of highly turbulent under-expanded hydrogen and methane jets under various nozzle pressure ratios and ambient pressures

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### ABSTRACT

The current study used large eddy simulations to investigate the sonic and mixing characteristics of turbulent under-expanded hydrogen and methane jets with various nozzle pressure ratios issued into various ambient pressures including elevated conditions relevant to applications in direct injection gaseous-fuelled internal combustion engines. Due to the relatively low density of most gaseous fuels such as hydrogen and methane, DI requires high injection pressures to achieve suitable mass flow rates for fast in-cylinder fuel delivery and rapid fuel-air mixing. Such pressures typically form an under-expanded fuel jet past the nozzle exit. Test cases of hydrogen injection with nozzle pressure ratio (NPR) of 10 issued into quiescent air with pressure  $P_{\infty} \approx 1$ , 5 and 10 bar were simulated. Direct comparison between hydrogen and methane jets with NPR = 8.5 and P\_{\infty} \approx 1 was also made. The effect of ambient pressure on features of transient development of the near-nozzle shock structure and tip vortices (vortex ring) was investigated. It was observed that at constant NPR, higher ambient pressure resulted in slightly faster formation of the Mach reflection and shorter Mach disk settlement time. Different mechanisms were observed between hydrogen and methane with regards to transient formation of their initial tip vortex rings. It was found that the initial transient tip vortices of hydrogen jets may also contribute to the flow instabilities at the boundary of the intercepting shock and, unlike for methane, promote fuel-air mixing before the Mach reflection. It was also shown that the near-nozzle shock structure was only affected by NPR regardless of the ambient pressure. Furthermore, no flow recirculation zone was found just downstream of the Mach disk, a finding comparable to all previous experimental investigations. Also, it was observed that a locally richer mixture was created for jets with higher NPR or with higher ambient pressure at constant NPR. Based on the results of the current study, correlations were proposed for the shock cell spacing and jet tip penetration of highly under-expanded jets issued from millimetre-size circular nozzles.

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Latin symbols and abbreviations $P_{sw}$ pressureAshock upstream condition $P_A$ shock upstream pressureAMGalgebraic multigrid $P_A$ shock downstream pressureBshock downstream condition $PV$ particle image velocimetryAUSMadvection upstream splitting methodSGSsub-grid scale $C_A$ coefficient of the new correlation of the jet tipttime after start of injection $C_W$ constant of Mach disk height correlationTtemperature $C_g$ specific heat $T_{co}$ ambient temperature $C_f$ coefficient in jet penetration correlation $U_1$ nozzle exit velocity $C_T$ coefficient of Mach disk width correlation $U_1$ nozzle exit velocity $C_T$ coefficient of Mach disk width correlation $U_1$ nozzle exit velocity $C_T$ coefficient of molecular diffusivity $Y_c$ scalar mass fraction $D_1$ nozzle exit diameter $X$ mole fraction $D_1$ coefficient in shock spacing correlation $Z_{tip}$ jet tip penetration $H_2$ hydrogen $Z_{tip}$ jet tip penetration $H_2$ kadch disk height $T_c$ scalar mass fraction of the inspecies $D_1$ coefficient of molecular diffusivity $Y_c$ scalar mass fraction of the nozzle exit $H_2$ hydrogen $Z_{up}$ jet tip penetration $H_2$ hydrogen $T$ scaling constant $K$ coefficient in shock spacing correlation $T$	Nomenclature	P <sub>0</sub>	upstream (nozzle) total pressure; injection
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P pressure	NPR nozzle pressure ratio	μ	uyilailie viscosity
	P pressure	ω	vorticity magnitude

### Introduction

### Gaseous fuelling

One of the proposed solutions to strengthen security of fuel supply and comply with international obligations for reduction of carbon-based emissions is to diversify towards use of more sustainable fuels and cleaner energy sources. More than a few alternative liquid and gaseous fuels have been recommended for spark-ignition internal-combustion engines. Gaseous hydrogen (H<sub>2</sub>) has been proposed as, ideally, the most promising carbon-free alternative particularly for road transportation if produced in a sustainable manner. Development of hydrogen-fuelled spark-ignition engines has been investigated experimentally and computationally by various research groups predominantly since the beginning of the past decade [1]. However, the technology of hydrogen-fuelled IC engines has not yet been commercialized due to various technical and political obstacles including: absence of fully

developed high-pressure hydrogen injectors with the necessary degree of durability, issues with on-board hydrogen storage and high-pressure fuel delivery systems with suitable crashworthiness characteristics, difficulties in mass production of hydrogen in clean and sustainable ways, the need for significant infrastructural investments for worldwide hydrogen distribution networks, etc. For the past twenty years or so the use of hydrogen has also been widely researched for fuel-cell powered vehicles. However, despite the relatively high efficiency of fuel cells, their manufacturing cost is still expensive and there are also several remaining technical challenges related to their performance under a range of conditions, condensation issues, etc. Therefore, the concept of a hydrogen-fuelled combustion engine is still quite appealing for future application on a commercial scale. On the other hand, methane, in the form of compressed natural gas (CNG), has been used on a commercial scale as a relatively cleaner and cheaper alternative fuel for road transportation and power generation [2].

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