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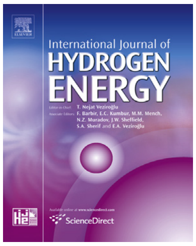

Gas dynamics and flow characteristics of highly turbulent under-expanded hydrogen and methane jets under various nozzle pressure ratios and ambient pressures

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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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Nomenclature

Latin symbols and abbreviations

A	shock upstream condition
AMG	algebraic multigrid
B	shock downstream condition
AUSM	advection upstream splitting method
C_A	coefficient of the new correlation of the jet tip penetration
C_W	constant of *Mach* disk height correlation
C_f	coefficient in jet penetration correlation
C_p	specific heat
C_t	coefficient in jet penetration correlation
C_H	Constant of *Mach* disk width correlation
CFD	computational fluid dynamics
CNG	compressed natural gas
D	nozzle exit diameter
D_i	coefficient of molecular diffusivity
DI	direct injection
DNS	direct numerical simulation
H_2	hydrogen
H_{disk}	*Mach* disk height
IC	internal combustion
K	coefficient in shock spacing correlation
K_m	kinematic momentum flux
LES	large eddy simulation
L_s	shock cell spacing
$\dot{M}$	momentum flux
Ma	*Mach* number
Ma_1	Mach member at the nozzle exit
Ma_{disk}	*Mach* number at the *Mach* reflection
Ma_A	shock upstream *Mach* number
Ma_j	jet fully expanded *Mach* number
NPR	nozzle pressure ratio
P	pressure
P_0	upstream (nozzle) total pressure; injection pressure
P_∞	static ambient pressure
P_A	shock upstream pressure
P_B	shock downstream pressure
PIV	particle image velocimetry
SGS	sub-grid scale
t	time after start of injection
t_0	nominal integral time scale
T	temperature
T_0	upstream total temperature
T_∞	ambient temperature
U_1	nozzle exit velocity
U_A	shock upstream velocity
W_{disk}	*Mach* disk width
WALE	wall-adapting local eddy-viscosity
X	mole fraction
Y_c	scalar mass fraction
Y_i	mass fraction of the i^{th} species
Z	axial distance from the nozzle exit
Z_{tip}	jet tip penetration

Greek symbols

β	angle of inclination in shock
Γ	scaling constant
γ	ratio of specific heats
η_g	Taylor microscale
η_k	Kolmogorov length scale
η_L	integral length scale
θ	shock deflection angle
ρ	density
ρ_∞	ambient density
λ	jet wavelength
μ	dynamic viscosity
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_2) 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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