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Large-eddy simulation on the effect of injection pressure and density on fuel jet mixing in gas engines

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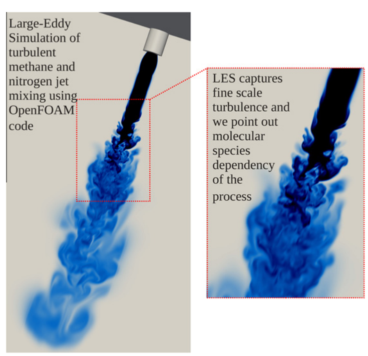
HIGHLIGHTS

- One of the first LES studies on highly underexpanded supersonic fuel jets.
- Gas molecular weight has a strong effect on the mixture quality.
- The density landscape inside the jet depends strongly on the density of injected gas.
- Production rate of lean mixture parts strongly influenced by gas molecular weight.
- The analysis gives consistent evidence that a lower density jet may impose more rapid mixing.

GRAPHICAL ABSTRACT



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ABSTRACT

Direct injection (DI) natural gas engines are modern engine concepts providing clean combustion and high fuel efficiency. Even at high injection pressures, such engines operate at heterogeneous/stratified fuel/air mixture conditions due to the relatively short mixing time of the fuel jet. The sub-optimal fuel–air mixture results in emissions of unburnt hydrocarbon (UHC). In particular, one of the most severe UHC emission is the release of the unburnt greenhouse gas methane (CH_4) into the atmosphere (methane slip). To better understand the origin of methane slip, in-depth knowledge of the turbulent mixture formation process is required. It is therefore critical to model the turbulent fuel jet using state-of-the-art computational fluid dynamics (CFD) methods with high time and space accuracy. In the present study, the penetration and mixing of non-reacting methane and nitrogen jets are simulated and compared. Nozzle pressure ratios between 4.5 and 10.5 are investigated with respective Reynolds numbers of the order 100,000. Based on these results, novel information is provided in terms of: (1) demonstration of the influence of the fuel molecular mass, and the injection pressure on turbulent mixture formation in highly underexpanded jets, and (2) understanding of the fuel air mixing dynamics for transient injection. The results indicate that, typically, the CH_4 jet mixes faster than the heavier N_2 jet. Investigation of the average density distribution explains the mixing differences.

1. Introduction

The limitations of conventional oil extraction and the recently growing recognition on unconventional sources of gas, such as shale gas in the United States, has made natural gas (NG) an

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economically attractive fuel for power production [1]. The molecular composition and quality of NG varies significantly, yet, commercial NG is mainly composed of methane (70–95%) and heavier hydrocarbons (primarily ethane and propane) as well as smaller amounts of hydrogen, nitrogen, and carbon monoxide for instance [2–4]. In addition to NG, gaseous fuels of interest are for instance renewable biogases [5,6] as well as gases produced with gasification products or hydrogen enriched fuel blends [7,8]. Out of all hydrocarbons, the methane molecule (CH_4) has the highest H/C ratio indicating lower carbon dioxide emission (per MJ-equivalent) in comparison to traditional hydrocarbon fuels [2]. Furthermore, in contrast to conventional diesel/gasoline/heavy fuel oils, NG combustion secures minimal SO_x and particulate matter (PM) emissions [4]. Thereby NG is a tempting alternative fuel for the marine industry, in particular for ships circulating in the environmental coastal area or via the artic sea routes in the near future [9]. Such issues show the demand for a wider usage of NG fed diesel engines, also referred to as gas engines.

Gas engines can be divided into the direct injection (DI) and the port injection (PI) concepts whereas the fuel can be ignited either by the spark ignition (SI) or by the compression ignition (CI) mechanism [2]. In the PI engine the gas is injected into the intake manifold and premixed before entering the cylinder. Although PI engines have been investigated quite extensively, they suffer from low volumetric efficiency due to reduction of the intake air by the volume of the injected fuel. PI engines also typically suffer from relatively strong cycle-to-cycle variations [3]. The DI concept remedies these problems by injecting the fuel directly into the engine cylinder through a gas injector similar to the conventional diesel injectors [2]. However, in contrast to the diesel engine, in a DI gas engine it is relatively difficult to ignite the gas by the temperature rise during the compression stroke. Thereby, the fuel–air mixture needs to be ignited either with a spark or another high cetane number fuel injected late in the compression stroke [2]. The usage of two fuels, a primary fuel with low and a secondary fuel with high reactivity, is termed the dual-fuel (DF) concept. The DF technology is currently on of the most promising approaches for achieving a thermal efficiency comparable to diesel engines with low emissions [2]. The experimental DI-engine research includes gas engines operated on e.g. NG ignited with diesel fuel [2,10,11], and biogas (60% CH_4, 40% CO_2) ignited with various conventional liquid fuels [5].

Natural gas remains in the gaseous phase even at pressures relevant to fuel injection making injection of NG jet into the engine cylinder a specific challenge, in contrast to a traditional diesel fueled spray DI engine. In a DI gas engine the pre-mixing process can be typically divided into two stages: (1) free jet formation without jet-wall/jet-piston interaction, and (2) jet interaction with cylinder walls. In contrast to diesel sprays, NG jets are not able form a continuously burning diesel-like diffusion flame around the jet perifery since the flame blowout nozzle pressure ratio (NPR) limit of gaseous jets lies in the very low pressure regime [12]. Thereby, DI gas engines are operated typically in the partially premixed combustion (PPC) regime with a broad fuel air ratio (ϕ) distribution including very fuel rich areas in the jet core. While the average global fuel–air ratio (ϕ) analysis can provide a good understanding on engine emissions for conventional diesel and gasoline engines as well as pre-mixed combustion, such as CI-engines, it is more doubtful to use the global ϕ as a mixture quality indicator in partially premixed combustion (PPC). As a consequence, the study of gaseous fuel mixing with air is vital for modern gas engines and the present paper focuses on characterizing premixing of free jets without wall interactions.

In a DI gas engine several well-known aspects influence the local mixture quality which affects the gas engine emissions and efficiency: (1) in-cylinder turbulence level which depends on engine load, (2) turbulence induced by the fuel jet, (3) large scale flow motions, and (4) cylinder geometry. There are also other effects that have received somewhat less attention. For example, McTaggart-Cowan et al. [4] have discussed how gas species composition affects the NG density and may thereby influence the jet mixing. The same authors have also discussed the effect of high-pressure injection on compression-ignition, DI NG engine [13]. They pointed out that at high engine loads higher injection pressure may significantly reduce the number density and size of soot particles in the exhaust gases while at low loads no significant effects were noted. Ben et al. [14] studied injection of natural gas into a CI-engine demonstrating that continuous injection may lead to highly heterogeneous mixture lasting even until the end of the compression stroke. Also the fuel injection timing is very important [7,15]. For example, Huang et al. [7] showed that an optimal injection timing can exist in SI DI-engine which leads to desirable properties including maximum heat release, high cylinder pressure and short combustion duration while maintaining low level of HC and CO emissions. According to Korakianitis et al. [2] further refinement, optimization and advancement of engine fuel injection systems is needed for the direct injection SI and CI technologies. Verhelst et al. [8] note the importance of optimizing injection pressure and nozzle design for achieving a desirable target mixture distribution. Thereby, the previous studies work as a motivation for the present study since, in the DI engine, they indicate the key importance of (1) local mixture quality on the combustion process, and (2) the fuel jet injection process.

A large majority of previous studies on high-speed supersonic compressible turbulent gas jets have focused on fuel injection in high speed flows and propulsion/hot exhaust jets for aeronautical and aerospace applications [16–22]. However, due to differences in operating conditions, these studies are not directly relevant to cold fuel injection in gas engines. There is therefore a need of studies focusing closely on NG injection in quiescent medium. Thereby, the present paper studies numerically non-reacting methane and nitrogen gas jet injection into a wall-bounded cylindrical volume assumed to be filled with nitrogen using computational fluid dynamics (CFD). The injection process features very rich physics including strong flow expansion, supersonic flow, shock waves, and turbulence. The present study focuses on smoothly contoured, converging nozzles where the flow can be characterized by defining three reference pressures: (1) upstream ‘reservoir’ pressure p_o and density ρ_o, (2) pressure and density at the nozzle exit p_1 and ρ_1, and (3) downstream pressure and density p_∞ and ρ_∞ inside the cylinder. The well known three flow regimes can be classified as follows [16]: (1) subsonic jet: $p_1/p_\infty = 1,\ 1 < p_o/p_\infty < 1.893$, (2) moderately underexpanded jet: $1.1 < p_1/p_\infty \leqslant 2,\ 2.08 < p_o/p_\infty < 3.8$, and (3) highly underexpanded jet: $2 < p_1/p_\infty,\ 3.84 < p_o/p_\infty$. The term ‘underexpanded’ is used because the gas pressure at the nozzle exit is higher than the ambient value p_∞. Such underexpanded jets exhibit shock cells comparable to nozzle diameter in size. For moderately underexpanded conditions oblique ‘diamond’ shocks can be observed whereas for the highly underexpanded jets normal shocks and the Mach disk appears [16].

For DI gas engine applications, underexpanded jets have been studied experimentally previously by a few authors [24–29]. For example, Ouellette and Hill [24] showed the tip penetration of underexpanded jets to scale with $\sim \sqrt{t}$. White and Milton [25] used Schlieren and shadowgraphy techniques to visualize appearance of the shock cells. The barrel shock development time was noted to be considerably high and last almost 5 ms which was essentially the whole duration of injection (DOI). Yu et al. [28,29] have investigated high-pressure non-reacting nitrogen jets with acetone feeding using the planar laser induced fluorescence (PLIF) method. It was shown that significant pressure losses of order 50% may occur inside the nozzle geometry. Further, Yu et al. noted that