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# Mixture formation in a direct injection gas engine: Numerical study on nozzle type, injection pressure and injection timing effects

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ABSTRACT

DI (direct injection) gas engines aim at providing clean and efficient combustion. Mixture quality control and hydrocarbon emission reduction are key development challenges in such engines. Here, a CFD (computational fluid dynamics) study of the DI gas injection process is carried out. The aim is to provide knowledge that aids e.g. engine designers in i) extending the lean limit at part load conditions via stratified mixtures, ii) mitigating incomplete combustion by improving mixing and eliminating fuel crevice flow. We investigate the sensitivity of the mixture formation process to nozzle type, injection pressure and injection timing. First, the present CFD method is discussed in free gas jet computations. For reference, we utilize planar laser induced fluorescence measurements and large eddy simulation results. After this, a total of 12 DI cases in moving mesh engine conditions are simulated. The main findings and novel results are listed as follows: 1) injection timing has a considerable influence on mixing rate, 2) efficacy of mixing mechanisms is highly nozzle type dependent, 3) jet-piston interaction may be utilized in the generation of a confining toroidal vortex in the piston bowl, 4) phase space analysis reveals two highly case dependent stages of mixture evolution.

## 1. Introduction

Increasingly stringent emission legislation forces the energy and transportation industries to develop alternatives for conventional engine fuels. Introduction of the so-called sulfur directive within the European Union [1] is one such administrative example. This development has, in part, led to the increased prominence of NG (natural gas) in a variety of internal combustion engine applications. The number of NG powered vehicles approximately doubled from 2007 to 2011 [2]. Energy networks that rely heavily on fluctuating renewable sources require highly responsive load balancing [3], for which NG engines are one alternative. With regard to fuel availability, many discovered gas resources are still unexploited [4]. Furthermore, novel sustainable fuel synthesis methods involving e.g. the utilization of carbon dioxide ($CO_2$) and water [5], are under constant development.

Methane ($CH_4$), the primary component of NG, has the highest molecular H/C ratio of all hydrocarbons. This lowers its $CO_2$ footprint in comparison to the longer chains found in conventional fuels. NG has been recognized as a means to achieve reduction in both nitrogen oxides ($NO_x$) and PM (particulate matter) [6]. Administered fuel quantities follow the lean-burn principle, where total AFR (air-fuel-ratio) exceeds the stoichiometric level. In addition to emission reduction, lean-burn improves engine efficiency, as a lean fuel-air mixture has a higher specific heat ratio than a stoichiometric mixture [7].

PI (port injection) is the dominant fuel supply method in contemporary NG engines. However, premixed PI charges limit volumetric efficiency as the injected fuel displaces a significant portion of the intake air volume prior to the intake valve closing [8]. Moreover, injecting fuel with the intake flow generates a mixture that is relatively homogeneous in the entire cylinder. This enforces an airflow restriction in part load operation, as it is not possible to

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burn fuel-air-mixtures that are excessively lean. The restriction effectively limits engine efficiency [9].

While lean premixed combustion decreases thermal $NO_x$ formation, a significant increase in AFR also increases UHC (unburned hydrocarbon) emissions [10]. This is a concern due to the established high global warming potential of $CH_4$ [11]. Part load operating conditions are particularly prone to UHC emission formation, as low exhaust gas temperatures lead to poor catalytic oxidation of hydrocarbons [7]. Hence, it is important to ensure complete combustion within the cylinder. Crevice flows are a documented UHC source [12], with the space between the piston and the cylinder liner as one of the identified locations. Cycle-to-cycle variation effects, particularly important in lean combustion [13], also contribute to UHC.

The limitations of PI have naturally raised interest towards DI (direct injection). Today, DI engine research is actively conducted with many alternative fuels such as bioethanol [14], alcohol blends [15], LPG (liquefied petroleum gas) [16] and NG. With NG, many studies such as the one by Kalam and Masjuki [17] deal with gasoline engine conversions. In addition, much work has been devoted to a concept where fuel is injected very late in the compression stroke, with ignition supplied by a diesel spray. This technology is already utilized in commercial engines [18]. However, gas injection near TDC (top dead center) requires a very high injection pressure, placing a limitation on total efficiency. The present work concerns lower injection pressures with timing principles closer to those in GDI (gasoline direct injection).

GDI is known as a fuel consumption and emission reduction method in the automotive industry. Efficiency gains associated with GDI are partly due to the capability to form stratified mixtures [19]. Stratification means that the generated fuel-air-mixture is localized, allowing for more induced air and an extension of the lean limit. While this principle is not new to the field, stratified mixture formation techniques are continuously investigated in contemporary literature. Costa et al. [20] characterized mixture formation and early combustion behavior in a *wall-guided* configuration, where stratification is based on deflecting the fuel jet from a shaped piston wall. Park et al. [21] investigated a *spray-guided/jet-guided* principle, where fuel is injected towards the proximity of the ignition source. In the *air-guided* technique, in-cylinder charge motion is utilized in directing the fuel vapor to the desired combustion chamber region. Such effects were recently documented by Harshavardhan and Mallikarjuna [22] in a bowl-shaped piston configuration. As shown later in subsection 3.2, these stratification mechanisms are connected to the results of the present study.

Previous stratified NG DI studies report mixed observations: Kubesh [9] found conventional DI stratification unfeasible, Huang et al. [23] concluded that stratified NG combustion has great potential for practical use, and Baratta et al. [24] stated its potential for limiting fuel consumption. Shiga et al. [25] reported a significant lean limit extension. Despite these studies, relevant data on mixture formation remains scarce. Importantly, there is no established best practice on the subject, as the present literature provides few guidelines on injection techniques or suitable nozzle types.

The present study seeks to improve this situation by studying the influence of various injection-related variables in NG DI mixture formation. Computational aspects of gas DI in an engine environment have been extensively discussed by Baratta et al. [26]. This process is prominently characterized by high velocity underexpanded jets (Fig. 1), described by Crist et al. [27] and Donaldson et al. [28], among many others. While LES (large eddy simulation) is gaining popularity in many CFD (computational fluid dynamics) applications, LES of high-speed, compressible jets is still focused on basic academic cases. Our axisymmetric simulation setup includes a moving piston and a moving mesh, and we employ a RANS (Reynolds-averaged Navier–Stokes) methodology. A sector mesh is well suited for RANS computations since the time-averaged solution for the case is not expected to pose 3D features. Importantly, the sector mesh allows us to maintain a high cell density; the geometric scale-separation between the nozzle and the cylinder is in the order of 100, presenting a known computational challenge [30].

Recently, Yadollahi and Boroomand [31] carried out a computational investigation on the effect of combustion chamber shape on mixture formation in a NG DI engine, stating the need to match injection timing, combustion chamber geometry, injector type and its location for an optimal combustion process. The present study investigates nozzle type, injection pressure and injection timing effects on mixture formation. In particular, both circular and hollow cone nozzles are assessed with a realistic piston bowl. The added value of this work arises from the combined consideration of these parameters, allowing for examination on their superimposed effects. To the authors' knowledge, this is the first NG DI study where these parameters are concurrently investigated. The objectives of this paper are to

- Assess the sensitivity of mixing to nozzle type, injection pressure and injection timing changes
- Examine how differences in jet structure influence mixing mechanisms
- Identify configurations that promote i) homogeneous and ii) confined (stratified) charge formation
- Describe potential mixture confinement mechanisms
- Characterize how fuel mass is distributed in terms of AFR, and how these distributions evolve in time

The study context is a medium-speed marine-scale engine in a single part load operating point. Intake flow effects are left out of the scope of the present investigation. We begin by computing hollow cone and circular free jets in order to establish qualitative reliability for the engine compression stroke simulations. For reference, we utilize our previously documented PLIF (planar laser induced fluorescence) measurements [32] and high-resolution LES results [33]. A mesh dependence study is provided for engine compression stroke simulations. Following this, mixture formation simulation results are reported.

## 2. Methodology

### 2.1. Numerical framework

In the present computational setup (Star-CD v. 4.16), conserved quantities are discretized with the MARS (monotone advection and reconstruction scheme), with the exception of density, where a blend of central differencing and upwind differencing is used. Temporal discretization is performed with the implicit Euler method, while the compressible form of the PISO (pressure-implicit splitting of operators) algorithm is the utilized solver.

### 2.2. Turbulence modeling for jets

In free jet flows, properties of widespread turbulence models, particularly EVMs (eddy viscosity models), have been studied by several researchers. The standard $k-\varepsilon$ model has experienced many modifications, resulting in improved predictions of jet flows [34]. With engine-related simulations, the RNG (Renormalization Group) version was shown to possess superior accuracy for jet tip penetration prediction when compared with the standard $k-\varepsilon$ model [35].