

Assessment of Multiple Injection Strategies in a Direct-Injection Hydrogen Research Engine

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ABSTRACT

Hydrogen is widely considered a promising fuel for future transportation applications for both, internal combustion engines and fuel cells. Due to their advanced stage of development and immediate availability hydrogen combustion engines could act as a bridging technology towards a wide-spread hydrogen infrastructure. Although fuel cell vehicles are expected to surpass hydrogen combustion engine vehicles in terms of efficiency, the difference in efficiency might not be as significant as widely anticipated [1]. Hydrogen combustion engines have been shown capable of achieving efficiencies of up to 45 % [2]. One of the remaining challenges is the reduction of nitric oxide emissions while achieving peak engine efficiencies.

This paper summarizes research work performed on a single-cylinder hydrogen direct injection engine at Argonne National Laboratory. Several injection strategies, composed of injection angle and combination of primary and secondary injection, were evaluated and compared to single injection strategy as a baseline. Due to the limitations in injector flow rates the study mainly focused on an engine speed of 1000 RPM. It was found that multiple injection strategies have the potential of reducing nitric oxide emissions by up to 85 % compared to single injection while maintaining constant engine efficiency. Further improvements to injector technology will be required to expand the operating regime of multiple injection strategies to higher engine speeds.

INTRODUCTION

Hydrogen is widely considered an excellent alternative fuel and deemed one of the most promising energy carriers for a future transportation scenario [3]. During the past several decades extensive research of hydrogen as a fuel for use in internal combustion engines has been performed. Hydrogen direct injection (DI) was found to be a preferable mixture formation concept mainly due to the increased power density compared to port injection [4]. One of the major hurdles in developing hydrogen direct injection operating strategies has been the absence of reliable fuel injectors. The properties of hydrogen in combination with the increased fuel injection pressure of hydrogen direct injection concepts as well as the exposure of the fuel injectors to combustion temperatures and pressures present unique challenges for the injector development [2]. Only recent progress in the development of solenoid- as well as piezo-driven high-pressure hydrogen injectors has made DI combustion concepts a viable alternative to hydrogen port injection which has so far mainly been employed for demonstration vehicles and combustion engine research.

Hydrogen direct injection presents an additional degree of freedom for influencing the mixture stratification and hence the combustion process resulting in potential efficiency improvement and nitric oxide emissions reduction. In recent years several studies evaluating the impact of injector location [5], injector nozzle design and other influencing parameters like injection pressure have been published. It was also found that splitting the injection process into several events throughout the

compression and combustion phase can positively impact the emissions signature [6]. In addition research has been performed on optical engines operated with hydrogen direct injection [7,8] as well as understanding basic hydrogen injection phenomena [9] and improving simulation tools [10].

A general trend of nitric oxide emissions as a function of air/fuel ratio has been reported by numerous authors and is well understood and established in the hydrogen community [e.g. 11, 12, 13, 14]. The general trend holds true for homogeneous mixture resulting from hydrogen port injection as well as early direct injection, however, the absolute level of NO_x emissions varies slightly. Air/fuel ratios below the critical threshold around $\Phi \sim 0.5$ result in extremely low nitric oxide emissions even without aftertreatment. A dramatic increase in NO_x emissions can be observed once the critical limit is exceeded with peak NO_x values reported in an air/fuel ratio regime around 0.8. Further increasing the air/fuel ratio towards stoichiometric operation results in decreased nitric oxide emissions likely due to the reduced amount of excess oxygen available. Vehicles employing operating strategies that avoid the NO_x critical regime have been demonstrated to be able to operate at NO_x emissions levels that are only a fraction of the most stringent emissions regulations [15].

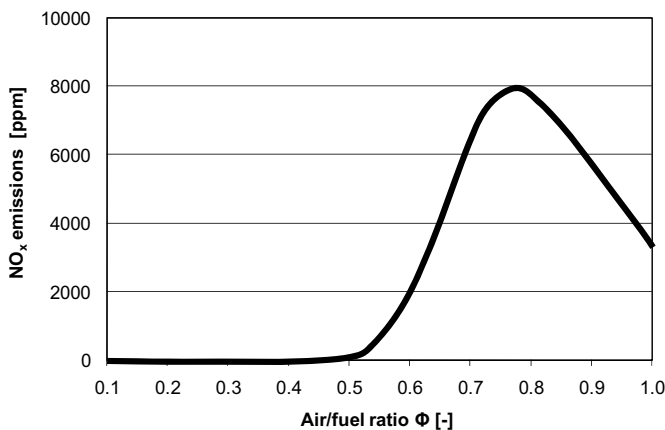


Figure 1: NO_x emissions as a function of air/fuel ratio for homogenous mixtures

Although this general trend only applies to homogenous mixture on a large scale, it can be used to explain the impact of stratification with locally richer and leaner mixtures on the overall emissions signature for direct and multiple injection cases.

EXPERIMENTAL SETUP

The impact of multiple injection strategies for various injection directions with a centrally located high-pressure fuel injector is evaluated. In addition to injection direction the impact of various distributions of fuel injected during the primary and secondary injection pulse is assessed and compared to a single-injection strategy. In order to reduce the complexity of the injection process for simulation purposes and to simplify the jet penetration

structure inside the combustion chamber a single-hole injector was selected for this particular study.

The engine that was used to perform the studies is a single-cylinder research engine. The main specifications for the engine are summarized in Table 1.

Table 1: Engine specifications [16]

Engine manufacturer	Ford Motor Company
Displacement (l)	0.5
Compression ratio	11.5:1
Bore/Stroke (mm)	89/79.5
Valve Train	4V Dual Overhead Cam (DOHC)
Intake Valve Timing	IVO=15° CA BTDC, IVC=35° CA ABDC
Exhaust Valve Timing	EVO=45° CA BBDC, EVC=10° CA ATDC
Peak cylinder pressure (bar)	100
Speed Range (RPM)	800-6000
Hydrogen measurement	Micro-motion Coriolis Meter
Injector – Direct Injection	Westport

The engine was specifically designed for hydrogen operation and can be operated with hydrogen port injection as well as hydrogen direct injection. A hydrogen supply system with an integrated coriolis meter was used to deliver and meter the hydrogen flow to the engine. The injector used for this study is a solenoid operated injector manufactured by Westport Innovations Inc.

TEST PLAN

With hydrogen port injection there is a considerable time period available between the injection event and the start of combustion which is generally triggered by a spark plug. Therefore the resulting hydrogen/air mixture is expected to be fairly homogeneous. There are certain influencing parameters on the mixture homogeneity with port injection, like injection pressure, valve timing, nozzle design and location of the injector within the intake manifold. These parameters have been optimized mainly to avoid abnormal combustion.

However, direct influence on mixture stratification can only be taken when the fuel is injected into the combustion chamber. Direct injection (DI) strategies open up a whole array of parameters that can be used to optimize the injection strategy. Some of the most dominant parameters have been identified as

- Injection timing
- Injection pressure
- Injector location
- Injector/jet orientation
- Injector nozzle design
- Injection strategy

This variety of parameters makes it virtually impossible to evaluate all possible combinations. Also, basic trends for individual parameters have been reported in the literature. However, these basic trends have not been proven to hold true when simultaneously varying combinations of the above mentioned characteristics.

In order to gain a better understanding of the impact of certain parameters and their interactions a test plan was developed that included variation of injection strategy and injection timing as well as injector/jet orientation while keeping all other parameters constant. Results presented in this paper are based on operation with hydrogen direct injection with central injector location. The hydrogen injection pressure was held constant at 100 bar.

NOZZLE DESIGN AND ORIENTATION

A simple injector nozzle design with a single injection hole was chosen. The injection hole with a diameter of 1.375 mm is located under an angle of 50° to the injector axis. The injector was mounted in central location adjacent to the spark plug. A schematic of the injector location and the direction of the injection jet relative to the injector axis are shown in Figure 2.

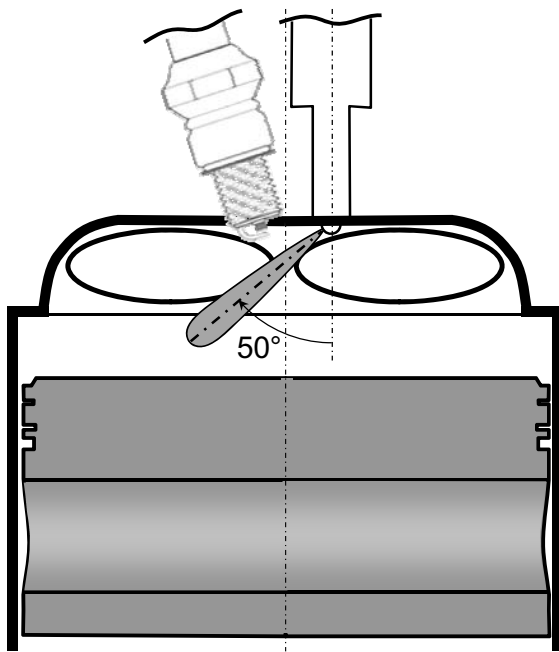


Figure 2: Orientation of the injector jet relative to the injector axis

The single-hole design was purposely chosen to simplify the setup and guarantee a single injection jet avoiding any jet-to-jet interaction inside the combustion chamber [17] or the so-called Coanda effect [18]. Various injector jet orientations were investigated as part of this study. In order to do so, the injector with its axis parallel to the cylinder axis was rotated and clamped in certain radial position. In order to identify the injection direction, it was measured relative to the location of the spark plug. An injection angle ϕ was defined to distinguish between injection directions with $\phi=0^\circ$ referring to the injection direction towards the spark plug (see Figure 3). Injection directions of 0, 45, 90, 180, 270 and 315° were investigated. These injection directions can best be described as:

- $\phi=0^\circ$ Injection towards the spark plug
- $\phi=45^\circ$ Injection towards the intake valve
- $\phi=90^\circ$ Injection towards the intake quenching zone

- $\phi=180^\circ$ Injection away from the spark plug
- $\phi=270^\circ$ Injection towards the exhaust quenching zone
- $\phi=315^\circ$ Injection towards the exhaust valve

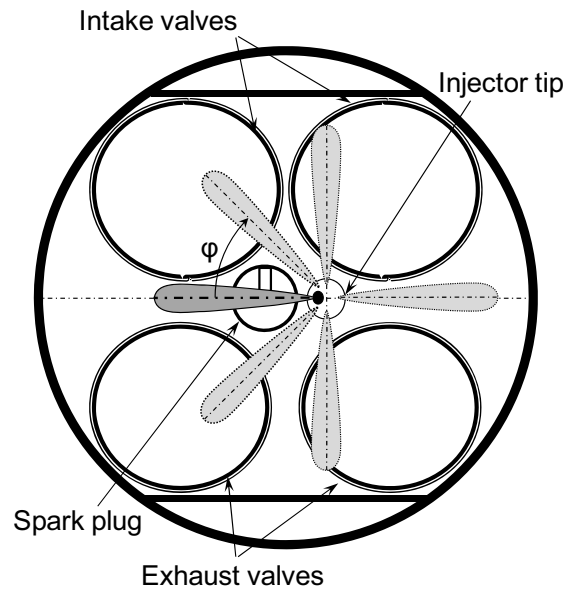


Figure 3: Bottom view of combustion chamber showing the various injector jet directions

INJECTION STRATEGIES

Several hydrogen direct injection studies confirmed the correlation between engine load (which correlates to air/fuel ratio for unthrottled operation), injection timing and nitric oxide emissions [12, 16]. At low engine loads and hence lean air/fuel ratios early direct injection which results in lean homogeneous mixtures results in low NO emissions. Once a certain load or air/fuel ratio is exceeded ($\Phi \sim 0.5$) the nitric oxide emission increase dramatically with a maximum around $\Phi \sim 0.8$ and decrease slightly when approaching stoichiometric mixtures. This basic trend holds true for hydrogen port injection as well as early hydrogen direct injection due to the resulting fairly homogeneous mixture at start of combustion. Late direct injection just before spark timing was generally found to exhibit an opposite trend in terms of NO_x emissions. The stratification would lead to increased NO_x emissions at low engine loads and a significant reduction at high engine loads compared to early injection.

Figure 4 shows a schematic of above mentioned operating strategies and also outlines the multiple injection strategies tested in this particular study. The basic idea of multiple injections is to create a lean homogeneous mixture that can be combusted without creating nitric oxide emissions while adding additional hydrogen during the actual combustion event. Depending on the spark timing relative to the start of the second injection one can further differentiate whether or not the mixture is already ignited at the start of the second injection.