

Study of Basic Injection Configurations using a Direct-Injection Hydrogen Research Engine

Thomas Wallner
Argonne National Laboratory

Abhijeet M. Nande and Jeffrey D. Naber
Michigan Technological University

ABSTRACT

The application of hydrogen (H_2) as an internal combustion (IC) engine fuel has been under investigation for several decades. The favorable physical properties of hydrogen make it an excellent alternative fuel for fuel cells as well as IC engines and hence it is widely regarded as the energy carrier of the future. The potential of hydrogen as an IC engine fuel can be optimized by direct injection (DI) as it provides multiple degrees of freedom to influence the in-cylinder combustion processes and consequently the engine efficiency and exhaust emissions.

This paper studies a single-hole nozzle and examines the effects of injection strategy on engine efficiency, combustion behavior and NO_x emissions. The experiments for this study are done on a 0.5 liter single-cylinder research engine which is specifically designed for combustion studies and equipped with a cylinder head that allows side as well as central injector location. A single-hole nozzle was placed in central location next to the spark plug and the fuel jets were oriented in a variety of different directions. Tests were conducted at different load points for all the injector orientations and the effects of varying the start of injection (SOI) timing on engine efficiency, combustion durations and NO_x emissions were studied. The results show that the engine efficiency and NO_x emissions are sensitive to the orientation of the fuel jets and the sensitivity varies with respect to different load conditions.

INTRODUCTION

The current crude oil crisis, ever rising gas prices and the hazardous impact of pollution on the environment have put increasing pressure on scientists and engineers to increase the use of alternative fuels in IC engines. An excellent alternative fuel which provides a good solution to the above mentioned problems is hydrogen. Its application as an IC engine fuel has been studied for several decades and researchers have provided extensive reviews of the available literature [1].

This paper studies a single-hole nozzle and examines the effects of the injection strategy on engine efficiency, combustion behavior and NO_x emissions. The experiments for this study are done on a 0.5 liter single-cylinder research engine which is specifically designed for combustion studies and equipped with a cylinder head that allows side as well as central injector location. A single-hole nozzle was placed in central location and the fuel jets were oriented in various different directions. Tests were conducted at different load points for all the positions and the effects of varying the start of injection (SOI) timing on engine efficiency, combustion durations and NO_x emissions were studied.

EXPERIMENTAL SETUP

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. The engine was specifically designed for hydrogen operation and can be operated with hydrogen port injection as well as

hydrogen direct injection. 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. 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.

Table 1: Engine specifications [2]

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
Speed Range (RPM)	800-6000
Peak cylinder pressure (bar)	100
Hydrogen measurement	Micro-motion Coriolis Meter
Injector – Direct Injection	Westport

DETAILS ON NOZZLE ALIGNMENT

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. As mentioned earlier 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 1.

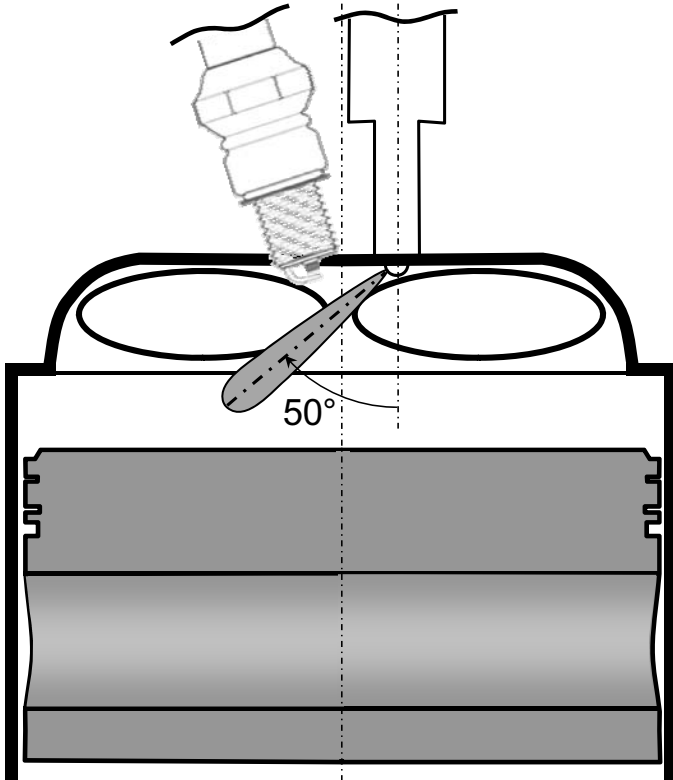


Figure 1: Orientation of the injector jet relative to the injector axis

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 [3]. Various injection directions were investigated as part of this study. In order to do so, the injector with its axis parallel to the cylinder axis could be rotated and clamped in any 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 directions towards the spark plug (see Figure 2). 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

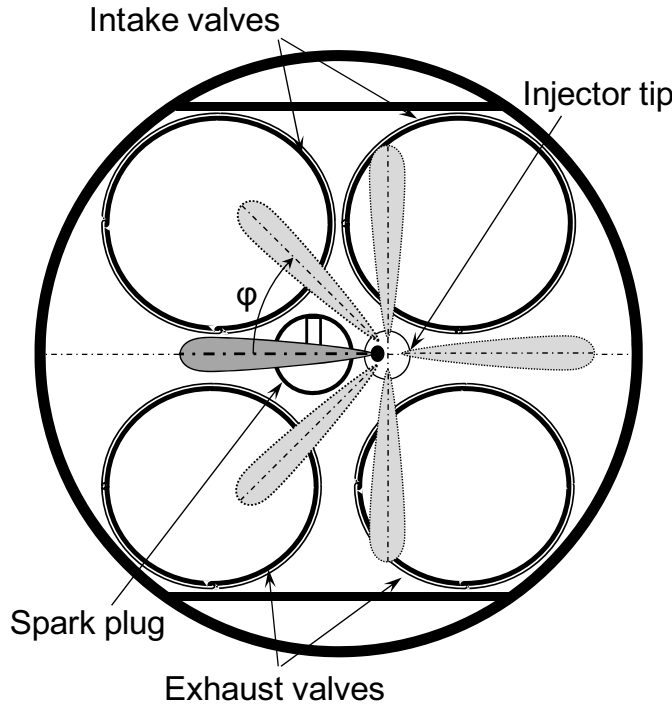


Figure 2: Bottom view of combustion chamber showing the various injector jet directions

TEST PLAN

The test plan for this study included variation of the injection direction with 6 defined cases as described above. In order to fully investigate each configuration a sweep of start of injection (SOI) was performed for each injection direction. This sweep was started out with early injection shortly after intake valve closing (SOI=140°CA BTDC) and SOI was retarded with a step width of 20°CA until the end of injection coincided with spark timing or stable combustion could not be maintained. Combustion is generally considered stable if the coefficient of variation of indicated mean effective

pressure does not exceed a certain threshold. It was observed that retarding the SOI for certain configurations resulted in misfires and incomplete combustion events with unburned hydrogen exceeding 20,000 ppm. No data was recorded at these points to avoid creation of ignitable mixture in the exhaust and these operating points were considered unstable. The engine speed was held constant at 2000 RPM while varying engine loads of 2.5, 4, 6 and 8 bar indicated mean effective pressure (IMEP). In addition to the injection strategy operating points with different spark timings were recorded for each case.

RESULTS

This comprehensive study resulted in a total of more than 400 individual operating points at 4 distinct engine loads. Figure 3 shows the range of achievable indicated thermal efficiencies for the different load cases. A variation of the injection strategy (direction of injection jet as well as start of injection) in combination with adjustment of spark timing results in changes in indicated thermal efficiency of more than 8 %.

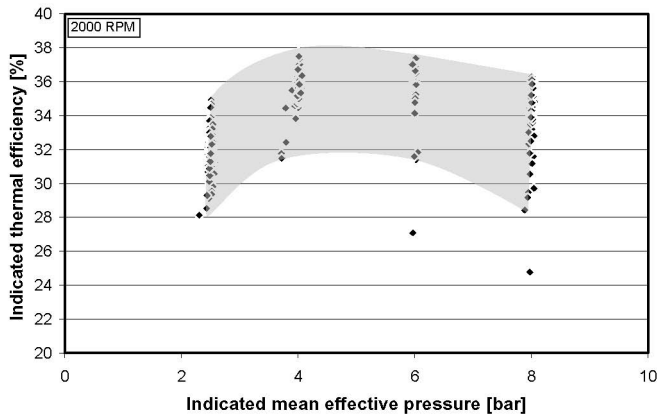


Figure 3: Efficiency range with variation of injection angle, start of injection and ignition timing

The influence of the injection strategy is even more pronounced when analyzing the resulting oxides of nitrogen (NO_x) emissions. In hydrogen direct injection operation the level of oxides of nitrogen emissions was found to be highly dependent on the mixture stratification [4]. Figure 4 shows the range of NO_x emissions for the different engine loads – at the high engine load of 8 bar IMEP NO_x emissions in a range from 500 ppm up to 6000 ppm are observed mainly depending on the start of injection as well as the spark timing [5].

Based on overall results at 2000 RPM a medium engine load point (6 bar IMEP) was selected for further investigation of the dominating factors for efficiency and emissions.

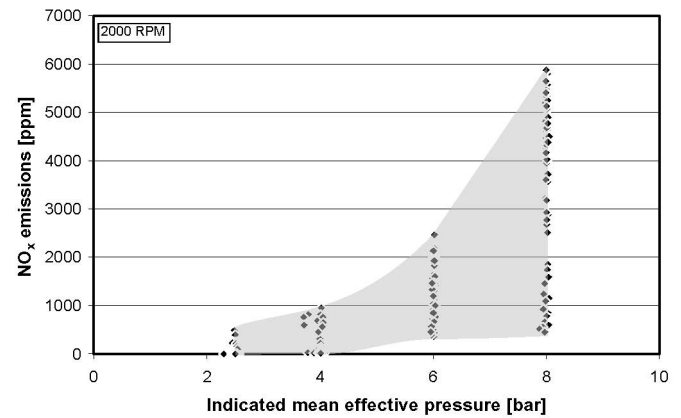


Figure 4: Range of NO_x emissions with variation of injection angle, start of injection and ignition timing

DETAILED ANALYSIS AT MEDIUM ENGINE LOAD

As mentioned earlier the major factors influencing engine efficiency are injection strategy and spark timing. For this study the injection strategy can be characterized as the injection angle (as defined earlier) and the start of injection. Both factors impact the mixture distribution inside the combustion chamber and therefore the efficiency and emissions characteristics. Figure 5 shows the indicated thermal efficiency for the medium load point (6 bar IMEP) at an engine speed of 2000 RPM. Colored dots represent configurations of actual test points – the results between test points were interpolated. The injection strategy is reflected as start of injection (SOI) on the x-axis and injection angle on the y-axis. For each combination the maximum brake torque (MBT) spark timing case is displayed. The efficiency ranges from 35 % to approximately 37.5 % and shows dependence on both, start of injection as well as injection angle. Injection towards the spark plug ($\phi=0^\circ$ and $\phi=360^\circ$ respectively) results in moderate impact of injection timing with an efficiency range between 36.5 % and 37.3 % and the highest efficiencies with SOI around 120°CA BTDC . The case with injection away from the spark plug ($\phi=180^\circ$) shows hardly any effects of injection timing with the indicated thermal efficiency almost constant around 36.5 %. A more pronounced effect of injection timing can be observed for the cases where the injection is pointed to the valves and quenching zones, both on the intake and exhaust side. The case with injection towards the intake valve quenching zone ($\phi=90^\circ$) with early injection (SOI= 140°CA BTDC) shows the lowest efficiency of all cases. Retarding the injection timing for this case as well as all other cases with injection towards the valves and quenching zones results in increased indicated thermal efficiencies.