In-Cylinder Fuel Reforming to Support High EGR Dilution in High Efficiency SI Engines

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Introduction

Legislative-driven targets worldwide have motivated considerable effort worldwide to decrease the CO_2 emissions from vehicles. Among other things, this includes improving the efficiency of spark-ignited engines. In this project we are attempting simultaneously improve the efficiency of SI engines through two mechanisms: high EGR dilution and exhaust heat recovery.

High levels of EGR dilution improve efficiency through several well-understood mechanisms. These are reduced pumping work at part load, an increased ratio of specific heats (γ) because of both a composition change and reduced cylinder temperatures, and there may also be an opportunity to increase compression ratio due to decreased knock propensity. While EGR dilution can improve efficiency, it also reduces the combustion stability, thereby limiting the amount that can be used and the efficiency benefit that can be realized.

The second strategy that we are pursuing simultaneously is exhaust heat recovery through thermochemical recuperation (TCR). With TCR, exhaust heat is used to drive endothermic reactions to convert thermal energy in the exhaust into chemical energy that can be burned in-cylinder. We are attempting to accomplish this using steam reforming, and in the scenario of 100% selectivity to steam reforming, we can expect to achieve up to a 25% increase in the lower heating value of the fuel, and up to a 14% improvement in the exergy of the fuel, as shown in Table 1.

Table 1. Steam reforming reactions for iso-octane and ethanol.

	Reforming Reaction	LHV Increase	Exergy Increase
Octane	$C_8H_{18} + 8H_2O \rightarrow 8CO + 17\ H_2$	25%	14%
Ethanol	$C_2H_5OH + H_2O \rightarrow 2\ CO + 4H_2$	24%	9%

At ORNL, we have developed a strategy that combines high levels of EGR with TCR for exhaust heat recovery. Further, because the products of steam reforming have a very high flame speed, particularly H_2, the reforming can be used to extend the dilution limit of the SI combustion. In this strategy, one of the engine cylinders breathes in oxygen-deficient products from the exhaust manifold and recompresses them in the presence of fuel. Ideally, the high temperature conditions in the absence of oxygen will drive reforming reactions and lead to TCR. If successful, this strategy will achieve waste heat recovery with a single work conversion device. A schematic of the strategy is shown in Figure 1.

Methodology

A modern, direct injection spark ignition engine with a displacement of 2.0L was modified to pursue an experimental investigation of this approach. The valve train was modified so that the cams actuated the valves on cylinders one through three only, and the valves for cylinder 4 were controlled by a fully flexible hydraulic valve actuation system. This allowed cylinder 4 to breathe in from the exhaust manifold, fuel to be injected for reforming into the hot, oxygen-deficient environment, and the resultant products to be exhausted into the intake system. Parametric sweeps at a constant brake mean effective pressure (BMEP) of 4 bar at an engine speed of 2000 rpm were conducted under globally stoichiometric conditions. The reformate products were characterized using an FTIR and a magnetic sector mass spectrometer for measuring H_2. Two different fuels were used in this study: ethanol and iso-octane. A schematic of this operating strategy is shown in Figure 1.

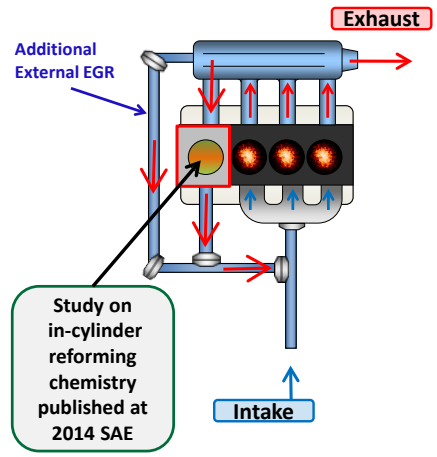

Figure 1. Schematic of the in-cylinder reforming strategy.

Results

Experimental cylinder pressure traces from this operating strategy are shown in Figure 2. The upper figure shows in-cylinder pressure trace for cylinders 1-3 and the lower figure shows the in-cylinder pressure trace for cylinder 4, the in-cylinder reforming cylinder. Cylinders 1-3 show a conventional SI combustion process, whereas cylinder 4 has no oxygen available to combustion the fuel, so the cylinder pressure is much lower. The sub-window in Figure 2 shows a parametric sweep of fuel injection duration into the reforming cylinder.

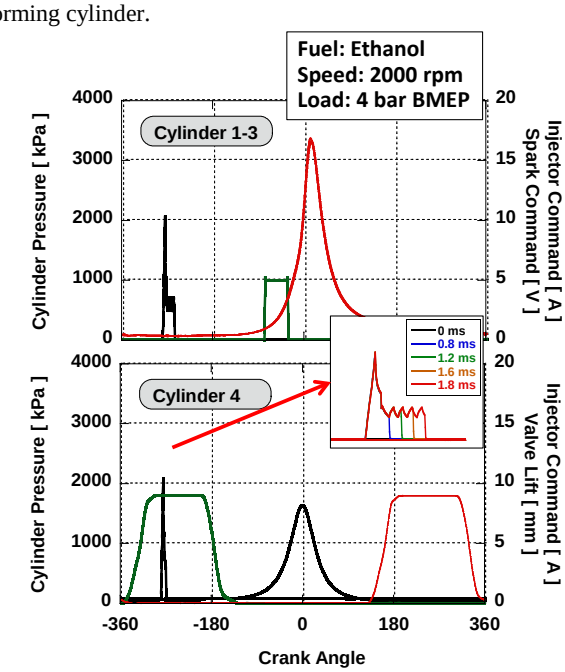

Figure 2. Cylinder pressure for the in-cylinder reforming strategy.

A comparison of efficiency for the in-cylinder reforming strategy relative to several different baseline cases, all at 2000 rpm 4 bar BMEP, is shown in Figure 3. For the conventional SI case, all of the cylinders are attempting to produce the same amount of power, but in the in-cylinder reforming strategy, only three of the cylinders are creating positive work, meaning that the individual cylinders are at a significantly higher load. Thus, a cylinder deactivation case was also added to the comparison, enabled by deactivating the cylinder with hydraulic valve actuation. Further, sweeps of external cooled EGR were performed with both the conventional SI strategy and the cylinder deactivation strategy. Ultimately, it was found that while the in-cylinder reforming strategy was significantly more efficient than the conventional SI strategy, consuming 9.4% less fuel to create the same power, the efficiency gain could be fully explained by the EGR in combination with the cylinder deactivation effect. No notable gain efficiency from improved dilution tolerance or thermochemical recuperation was observed.

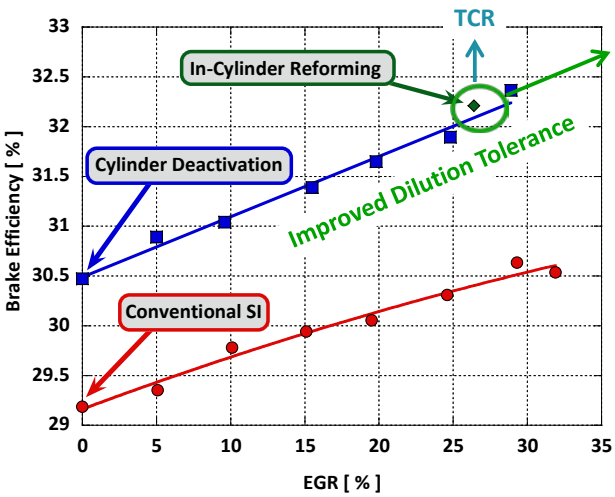

Figure 3. Efficiency comparison as a function of EGR for the in-cylinder reforming, cylinder deactivation, and conventional SI strategies.

Chemical speciation can be used to explain why the in-cylinder reforming strategy did not show an additional benefit over the cylinder-deactivation strategy with EGR. Figure 4 shows the amount of fuel, in this case ethanol, in the intake manifold as a function of injection duration. Instead of the being converted into reformate products, it was being exhausted from the reforming cylinder in an un-reacted state. This is also shown in Figure 5 by the amount of H_2 and CO formed by the reforming process. While there is some H_2 and CO present, the majority of the fuel is not converted to reforming products.

The reason for the lack of fuel conversion in the in-cylinder reforming process is that the in-cylinder temperature is not sufficiently high. Analysis of the thermal processes revealed that the heat losses in the exhaust manifold were higher than expected, resulting in an in-cylinder temperature that was only about 950K instead of the 1050K required for high fuel conversion.

To account for this, modifications have been made to the experimental setup to increase the temperature in the reforming cylinder. These included increasing the compression ratio of the reforming cylinder from 9.2:1 to 12.5:1, and providing an air injection system to allow for a small flow of air into the cylinder so that exothermic combustion reactions could increase the temperature to drive the endothermic reactions. These modifications did substantially increase the fuel conversion of the in-cylinder reforming process, with the addition of air in particular increasing the fuel conversion with both ethanol and iso-octane. However, despite the increase in fuel conversion, an efficiency gain through either TCR or an increased dilution tolerance has not yet been realized.

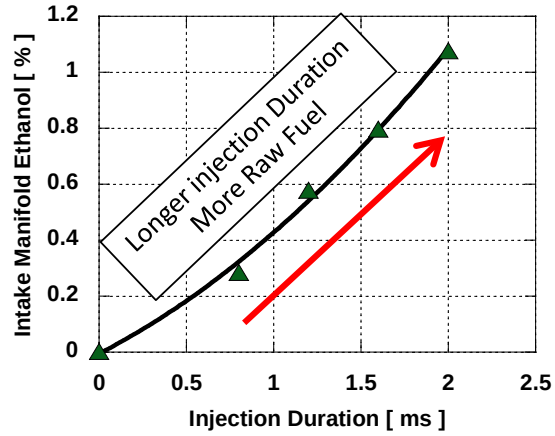

Figure 4. Unconverted fuel ethanol present in the intake manifold as a function of fuel duration injected into the reforming cylinder.

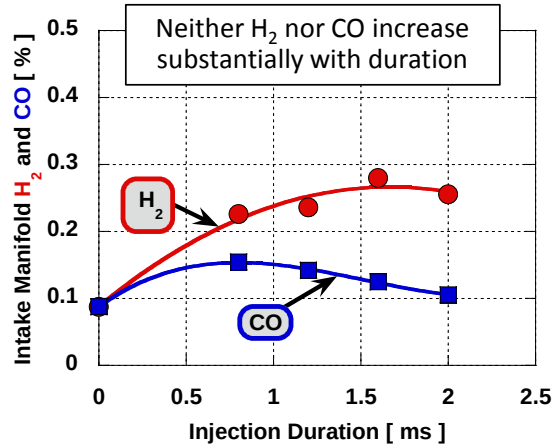

Figure 5. H_2 and CO present in the intake manifold, produced from in-cylinder fuel reforming, as a function of fuel duration injected into the reforming cylinder.

Conclusions

A multi-cylinder engine operating strategy has been developed to attempt to simultaneously operate with high levels of EGR dilution and achieve waste heat recovery through TCR. A unique, flexible engine experiments was developed at ORNL to perform parametric investigations with the strategy. Results show that by using the in-cylinder reforming strategy, the fuel consumption was decreased by over 9% compared to the baseline operation. However, additional analysis revealed that the efficiency benefit could be attributed to the EGR and cylinder deactivation effect rather than an extended dilution tolerance and TCR. Additional experiments, including some experimental modifications, are ongoing to clarify whether the potential benefits of this operating strategy can be realized.

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