

The Effect of Acetylene on Iso-octane Combustion in an HCCI Engine with NVO

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ABSTRACT

Prior studies have shown that fuel addition during negative valve overlap (NVO) can both increase temperature and alter composition of the charge carried over to main HCCI combustion. Late NVO fuel injection, i.e., near top dead center, can cause piston wetting and subsequent localized rich flames. Since acetylene is a product of rich combustion and is known to advance ignition, it is hypothesized that the species could play a chemical role in enhancing main combustion. The objective of this work is to quantify the effects of acetylene on HCCI combustion.

While the research topic is specifically relevant to NVO-fueled HCCI operation, the experiments are conducted without NVO fueling to avoid uncertainties of NVO reforming reactions. Instead, a single post-NVO injection of iso-octane fuels the cycle, and acetylene is seeded into the intake flow at varying concentrations to simulate a reformed product of NVO. Total chemical energy is held constant by adjusting injected mass of iso-octane to compensate for added acetylene. In addition, combustion phasing is held constant by adjusting intake temperatures. The temperatures required to achieve target phasing, as well as heat-release analysis, provide a measure of acetylene's enhancement of main combustion. Chemical kinetics simulations using a piston/cylinder reactor model add insight to the experimental results.

Results show that few-parts-per-thousand concentrations of acetylene reduce charge temperatures that are required in order to achieve target combustion phasing, increase peak heat-release rates, and improve combustion efficiency.

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INTRODUCTION

Homogenous-charge compression-ignition (HCCI) engine strategies have been researched extensively. Primary advantages of HCCI include high efficiency associated with unthrottled operation and volumetric combustion, as well as low engine-out emissions associated with dilute, low-temperature combustion [1,2,3]. The principal challenge to deploying HCCI engines is the difficulty in controlling combustion phasing and pressure rise rates.

For high-load operation, excessive pressure rise rates restrict the operating range, and researchers have employed strategies such as thermal stratification [4,5], boosted operation [6] and variable valve timing [7] to diminish the limitation. For low loads, combustion is limited by low charge temperatures that can lead to incomplete combustion and misfire. Such strategies as exhaust-gas recirculation, re-breathing, and recompression all make use of high residual fractions to enhance auto-ignition under light-load conditions. Retained residuals can affect combustion through modification of charge temperature, dilution, heat capacity, chemical reactivity, and stratification [4,5,8,9].

The recompression or negative valve overlap (NVO) strategy is of particular interest to the current study. In addition to retaining residuals, the NVO strategy enables the injection and reaction of fuel during the NVO period. This adds an additional thermal and a chemical mechanism for controlling main combustion. The thermal mechanism refers to charge heating associated with NVO reactions and the chemical mechanism refers to reactive product species of NVO reforming that are carried over to main compression. Both potentially influence main combustion phasing, peak burn rate, and burn duration [10].

Many investigators [1,2,3,8,10,11,12,13,14,15,16,17,18,19] have examined thermal effects of NVO fueling on main combustion. In those experiments, lean and near-stoichiometric conditions during NVO are typically selected to achieve high NVO combustion efficiencies that maximize thermal effects. Experiments designed to isolate chemical effects of NVO fueling are rarer [11,12,14,17]. By selecting oxygen-deficient or other special conditions during NVO, reforming reactions are promoted over heat release to emphasize chemical over thermal effects.

In spite of these research efforts, fundamental details of chemical enhancement of main combustion due to NVO fueling remain uncertain.

Prior experiments in our lab addressed the issue of thermal and chemical effects of NVO fueling [20]. In these experiments a small fraction of total fuel was injected during NVO and the resulting main combustion phasing was measured. Notably, we found a distinct difference between early and late NVO fuel injection. Fuel injected early reacted relatively completely during NVO, elevating charge temperatures and advancing main combustion phasing. In contrast, fuel injected late during NVO reacted less completely, i.e., produced less heat during NVO, but it still advanced main combustion as much or more than early NVO injection. From this, we concluded that carry-over chemical species played an important role in the late NVO injection experiments. We also observed that late NVO fueling, unlike early, produced conspicuous sooty flames, suggesting that the carry-over species could be products of localized rich combustion.

The above research motivates our current study of the chemical effect of a single hydrocarbon, acetylene, on HCCI combustion. Based on the fact that it is both a product of rich combustion [21,22] and a known combustion enhancer [23,24,25], we selected acetylene to represent reactive species that might be produced during NVO fueling and subsequently affect main combustion. The use of acetylene as a fuel or additive is not an entirely new idea. Swaminathan et al. [23] discussed the possible operation of a diesel engine using aspirated acetylene as the only fuel. They showed that acetylene combustion occurred early and the burn rate was faster compared to DI diesel operation. Lakshmanan et al. [24] seeded acetylene into the intake of a dual-fuel DI diesel engine and observed an increase in peak pressure, peak pressure-rise rate, and peak heat-release rate, as well as an advancement of combustion phasing. GM Research Laboratories patented a strategy using acetylene as an additive to enhance gasoline HCCI combustion [26]. Yu et al. [25] recently sampled NVO reformed products carried over to the compression stroke and found significant concentrations of acetylene. A chemical kinetics simulation of their experiment indicated that acetylene played an important role in the advancement of ignition timing observed in the experiment.

In our experiments, we have modified the usual protocol by eliminating the NVO fuel injection and replacing it with a combination of acetylene seeding plus increased intake temperatures. By removing the NVO fuel, we avoid the complex mix of reformed products so that we can focus on acetylene alone and observe its effect on main ignition. Any enhancement of main combustion over operation without the seed can be construed as a chemical effect of acetylene. In this way, the experiments can test the hypothesis that NVO reforming reactions might be used to assist control of low-load HCCI combustion. The desired practical goal of this

research is to help extend the low-load range of gasoline HCCI engines currently being developed.

EXPERIMENTAL APPROACH

The objective of these experiments is to quantify the effects of acetylene (C_2H_2) without interference from other species created during NVO fueling. Thus, as mentioned in the Introduction, we eliminate NVO fuel injection while simulating NVO production of acetylene by seeding it into the intake. To compensate for the missing sensible energy associated with NVO reactions, intake temperatures are elevated. To further simplify the chemistry, we use the single-component fuel iso-octane (C_8H_{18}) which is injected at intake valve opening (IVO) for all experiments. Experiments with no C_2H_2 seeding serve as a reference case for comparison against experiments with varying amounts of C_2H_2 seeding.

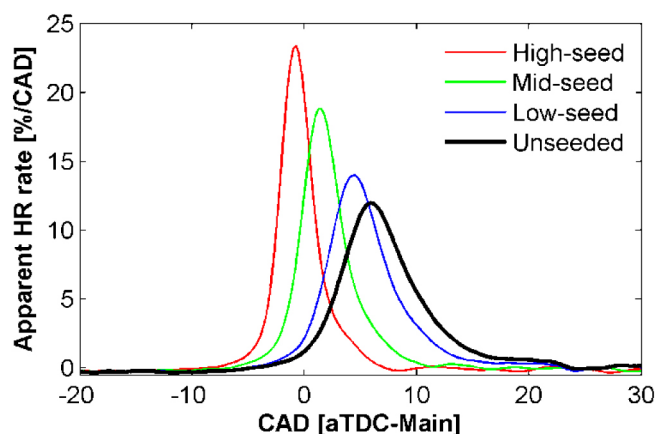


Figure 1. Apparent heat-release rate of main combustion for experiments with a constant intake temperature and constant C_8H_{18} injected fuel mass (rather than the constant phasing and constant energy conditions used below). For grayscale viewing, the unseeded case is at the bottom with the seeded cases positioned above in low-to-high order.

The engine operating protocol has been selected to highlight fundamental details of C_2H_2 addition and remove confounding influences. Figure 1 presents results of scoping experiments performed while maintaining a constant intake temperature and constant iso-octane mass injected per cycle. The enhancement of C_2H_2 seeding is obvious under these conditions. But since peak heat-release (HR) rates are influenced by both combustion phasing and total chemical energy, the graph actually over-states the impact of C_2H_2 . To remedy this, our data experiments have been conducted while holding constant the crank angle at which 50 % of main combustion has occurred (CA50). Furthermore, chemical energy is held constant by removing an energy-equivalent

amount of C_8H_{18} from the fuel-injection event as C_2H_2 is added to the intake stream.

ENGINE SPECIFICATIONS AND OPERATING CONDITIONS

Experiments are carried out in a single-cylinder automotive HCCI research engine configured for NVO operation. The GM prototype pent-roof head houses two intake valves and a single exhaust valve. A *negative* overlap of 150 CAD is achieved by early exhaust valve closing and late intake valve opening using short-dwell, low-lift cams. The selected valve timings retain approximately 50 % of the main charge during NVO. The engine's geometric compression ratio is 11.5, but comparison with a GT Power 1-D engine model [27] indicates that an effective value of 11.3 is better suited for experiment analysis. The engine can be configured for optical access, but for the current study, an all-metal configuration was used. Additional engine specifications are listed in Table 1.

Table 1. Engine specifications.

Displacement	0.633 L
Bore	92 mm
Stroke	95.25 mm
Effective compression ratio	11.3
Intake valve opening	75 CAD aTDC-NVO
Intake valve closing	-140 CAD aTDC-Main
Exhaust valve opening	140 CAD aTDC-Main
Exhaust valve closing	-75 CAD aTDC-NVO
Valve lift	3 mm

Iso-octane fuel is used in all the experiments described in this paper. This choice simplifies analysis of results and facilitates comparison with simulations and other experiments. To verify that results are representative of more conventional fuels, we performed several trials using a research gasoline and found trends similar to those presented here. Iso-octane is delivered to the cylinder by an 8-hole direct injector, centrally located in the head. Total chemical energy of the reactants C_8H_{18} and C_2H_2 is held constant at a value equivalent to 9.0 or 11.0 mg of C_8H_{18} per cycle - the different fueling rates allow us to compare results at two different light-load conditions.

Metering flows of pure C_2H_2 to obtain a range of known intake concentrations is challenging. The most convenient source of the gas is welding tanks, but output pressures are low for safety reasons, limiting the range of flows that can be measured using the most practical metering system, sonic orifices. Nonetheless, by selecting three small orifice sizes, we are able to generate a suitable range of C_2H_2 flows. Calibrating the orifices is done indirectly starting with a gas chromatograph/flame-ionization detector (GC/FID) located at Lawrence Livermore National Lab. This instrument is calibrated using commercial hydrocarbon gas standards, and it in turn is used to calibrate an emissions-bench FID located

in our engine lab. Figure 2 presents our uncorrected bench-FID measurements plotted against calibrated C_2H_2 concentrations. The greater-than-unity slope of the graph is due to known exceptional behavior of C_2H_2 in diffusion flames and agrees with published per-carbon response factors that must be applied to correct FID measurements of C_2H_2 [28]. As a final step, we use the corrected bench FID to calibrate our sonic orifices. Note that with our high residual gas fractions of approximately 50 %, in-cylinder C_2H_2 concentrations at IVC are about half the intake-system values.

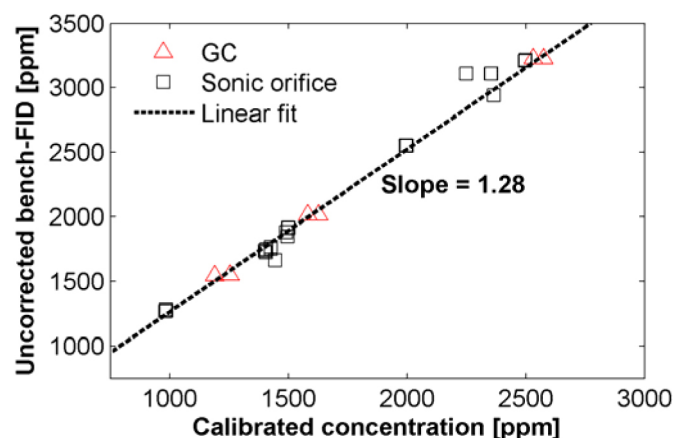


Figure 2. Correction of emissions-bench FID measurements of C_2H_2 . For the triangle symbols, x-axis concentrations represent measurements using a calibrated GC/FID, and y-axis concentrations are uncorrected emissions-bench FID measurements. For the square symbols, x-axis concentrations are determined from sonic orifice data. The latter are included to illustrate the repeatability of measurements reported in the paper; standard deviation of these measurements is 76 ppm.

Engine operating conditions are listed in Table 2. Heaters on intake system components maintain desired intake temperatures and an electronic regulator upstream of a sonic orifice meters air flow while maintaining the constant average manifold air pressure. A positive-displacement flow meter in the fuel line measures average fuel delivery per cycle. A piezo-electric transducer provides cylinder pressures recorded at $\frac{1}{4}$ -CAD increments. Thermocouples located just outside the intake and exhaust valves provide temporally averaged charge temperatures. A thermocouple inserted just below the surface of the combustion chamber roof provides a wall temperature used for engine warm-up and heat-transfer calculations. An emissions bench measures engine-out O_2 , CO, CO_2 , NOx, and unburnt hydrocarbon concentrations. The range of C_2H_2 concentrations noted in Table 2 was selected based on prior research at GM Research Laboratories [26]. Recently published experiments [25] measured in-cylinder concentrations of C_2H_2 that are about one-quarter of