

Effects of Secondary Air Injection During Cold Start of SI Engines

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ABSTRACT

An experimental study was performed to develop a more fundamental understanding of the effects of secondary air injection (SAI) on exhaust gas emissions and catalyst light-off characteristics during cold start of a modern SI engine. The effects of engine operating parameters and various secondary air injection strategies such as spark retardation, fuel enrichment, secondary air injection location and air flow rate were investigated to understand the mixing, heat loss, and thermal and catalytic oxidation processes associated with SAI. Time-resolved HC, CO and CO₂ concentrations were tracked from the cylinder exit to the catalytic converter outlet and converted to time-resolved mass emissions by applying an instantaneous exhaust mass flow rate model. A phenomenological model of exhaust heat transfer combined with the gas composition analysis was also developed to define the thermal and chemical energy state of the exhaust gas with SAI.

The study found that significant emissions reduction can be achieved with SAI by the thermal oxidation process prior to the catalyst, which results in higher exhaust gas temperatures and therefore enhances the chemical process inside the catalyst by faster catalyst light-off. The engine operation, with a relative air/fuel ratio 20% rich of stoichiometric and 100% secondary air, yielded the fastest catalyst light-off time of 4.2 sec. The SAI system reduced HC emissions by 46% to 88% and CO emissions by 37% to 93% compared with the normal operating conditions. The analysis showed that the post-catalyst HC emissions levels were optimized with secondary air flow rates corresponding to an overall exhaust lambda of 1.3. The improvement in the thermal oxidation reaction with the increased mixing rates upstream of the catalyst decreased the catalytic oxidation reaction due to the increased consumption of reactants upstream of the catalyst.

Therefore, the post-catalyst HC emission levels were not strongly affected by the mixing rates.

INTRODUCTION

The cold start emission problem has been known from the earliest days of engine emission control. However, until the late 1980s, the emissions technologies were primarily aimed at fully warmed-up engine conditions. The most significant gains could be made by the use of catalytic converters without the need to address the cold start issue. This very disparity eventually brought about a change of emphasis [1]: since exhaust gas after-treatment is now remarkably effective in reducing tailpipe-out emissions from warmed-up engines, increasing emphasis is being placed upon cold start emissions. Currently, the majority of the total HC and CO emissions during the FTP-75 are produced during the first 25 or so seconds of engine operation before the catalyst reaches its light-off temperature (~250°C) [2].

The cold start process of port-fuel-injected SI engines generally involves significant over-fueling in the intake port. This fuel enrichment provides a sufficient amount of vaporized fuel so that an acceptable degree of combustion stability and vehicle driveability can be assured during cold start. However, a sizeable portion of this excess fuel survives the combustion process unburned, and exits the cylinder with the bulk exhaust gas; therefore it contributes significantly to engine-out HC emissions [3, 4, 5]. Also, this fuel enrichment contributes to the paucity of exhaust oxygen, which limits the extent of exothermic chemical reactions in the exhaust port, manifold and catalyst. The injection of air into the exhaust system therefore could be an effective way to utilize additional thermal and chemical energy available in the exhaust gas during cold start.

The secondary air leads to two relevant definitions of lambda: “engine lambda (λ_{engine})” and “exhaust lambda (λ_{exhaust})”. These are defined in Eq. (1) and Eq. (2), respectively. The facility to adjust the latter independently of the former eases the engine calibration constraints [1]. The need to attain stoichiometric fueling as rapidly as possible is relaxed because sufficient air can always be added to compensate for the deficiency in oxygen in the engine-out exhaust gas.

$$\lambda_{\text{engine}} = \left(\frac{\text{Air}_{\text{intake}}}{\text{Fuel}} \right) / (A/F)_s \quad (1)$$

$$\lambda_{\text{exhaust}} = \left(\frac{\text{Air}_{\text{intake}} + \text{Air}_{\text{secondary}}}{\text{Fuel}} \right) / (A/F)_s \quad (2)$$

In general, the chemical reactions occurring in the exhaust system with secondary air injection can be categorized into two types of oxidation of reactants. One is the oxidation process that happens inside the exhaust port and manifold prior to the catalytic converter, which is referred to as “thermal oxidation” in this experimental study. The other is the oxidation of HC and CO that occurs inside the catalytic converter, which is significantly different from thermal oxidation due to the presence of a catalyst and is referred to as “catalytic oxidation” [6].

The work presented herein investigates and quantifies the effects of secondary air injection on the cold start emissions and catalyst light-off of a modern SI engine. Steady state experiments provided a basic understanding of the effects of SAI on exhaust gas temperatures and emissions. In a series of engine start-up experiments, exhaust gas emissions, gas heat transfer, and catalyst light-off performance were evaluated with various SAI strategies during the first 25 seconds following engine cranking. The thermal and chemical processes associated with SAI inside the exhaust system were investigated to fully exploit the simultaneous benefits of reducing exhaust gas emissions and improving catalyst light-off performance during cold start.

APPARATUS AND PROCEDURE

EXPERIMENTAL SETUP

Experiments were performed on a production port-fuel-injected SI engine (GM 2.2 liter L61 Ecotec engine). Additional engine details are given in Table 1. The engine was coupled to an eddy current dynamometer. The engine's starter motor was used for cranking operation with full control over the engine control module (ECM). This ECM was controlled and modified by a Delco Modular Development System (MDS). Each cylinder was equipped with a flush-mounted piezoelectric pressure transducer and

also an absolute pressure transducer was installed in the intake manifold runner. All tests were performed with unleaded test gasoline, which is commonly termed “Indolene”.

Table 1. Engine specifications

Ecotec 2.2-liter, 4-cylinder Engine Specifications	
Type	Naturally Aspirated, I-4
Displacement Volume (cc)	2189
Clearance Volume (cc)	65
Bore (mm)	86
Stroke (mm)	94.6
Connecting Rod (mm)	146.5
Wrist Pin Offset (mm)	0.8
Compression Ratio	10.0:1
Firing Order	1-3-4-2
Valve Configuration	16V DOHC
Valve Timing	IVO: 1° ATDC
	IVC: 49° ABDC
	EVO: 30° BBDC
	EVC: 13° ATDC

The engine's exhaust system consisted of a cast-iron manifold, a three-way catalytic converter and a muffler. The catalyst supplied with the engine was an active Ultra-Low-Emission Vehicle (ULEV) catalyst. The converter was 4.2 inches in diameter with 600 cells per inch and was composed of two bricks; the first was 2 inches in length and loaded with 3.5 grams of palladium (Pd) and the second brick was 4 inches in length and loaded with 1.5 grams of platinum (Pt) and 0.31 grams of rhodium (Rh). A thermocouple was embedded at the middle of each brick along the centerline of the catalyst. Pre-catalyst and post-catalyst gas samples were acquired approximately 4.7 inches from the bricks.

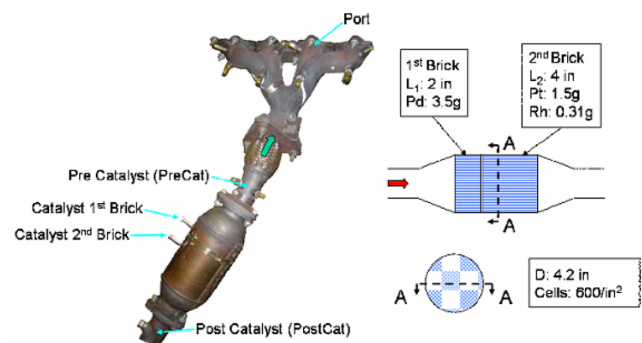


Figure 1. Schematic of exhaust system with three-way catalytic converter specifications

SECONDARY AIR INJECTION SETUP

A secondary air injection device was installed between the engine block and exhaust manifold as shown in Fig. 2. Secondary air was injected through a set of 8 tubes, with each tube directed straight towards each exhaust valve. To avoid possible back flow effects during the blowdown phase of the exhaust process, the tube design in this study had a closed end and two holes drilled on the side of the tube so that the secondary air was injected from the tube perpendicular to the exhaust gas flow. The secondary air flow rates were regulated by critical orifices, which were calibrated by a mass flow meter. Three values of secondary air flow rate were tested during the constant lambda start-up experiments. The same experimental setup outlined here was used for exhaust gas quenching experiments in which secondary air was replaced by nitrogen gas.

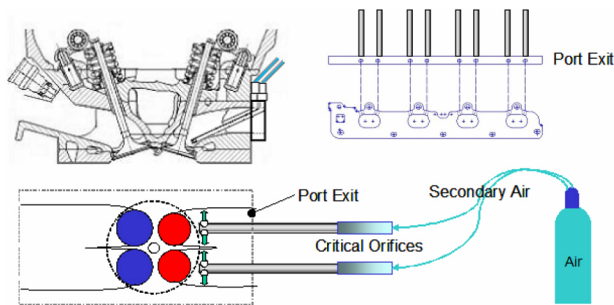


Figure 2. Overview of secondary air delivery system equipment (probes, critical orifices, etc.)

EXHAUST GAS MEASUREMENTS

Time-resolved HC, CO and CO₂ concentrations were measured simultaneously via a Cambustion HFR400 fast-response flame ionization detector (FFID) and a Cambustion NDIR500 fast-response non-dispersive infrared (NDIR) detector. Exhaust gas samples were acquired at the exit of each exhaust port, the pre-catalyst and the post-catalyst location with a time response on the order of a few milliseconds. Exhaust gas temperatures at several locations were obtained from type-K exposed-junction thermocouples with custom radiation shielding. Exhaust air/fuel ratio was measured by a universal exhaust gas oxygen (UEGO) sensor located at the exhaust manifold collector.

CONTANT LAMBDA ENGINE STARTUP

The continuously varying lambda values with a typical engine calibration during cold start introduce additional complexity in the emissions analysis with the secondary air injection strategy. Thus, engine start-up experiments were conducted with three different constant lambda start-up

strategies as shown in Fig. 3. Since the engine operations with the constant lambda trajectories produced relatively constant levels of exhaust emissions, the effects of SAI were more clearly observed with the constant lambda start-up processes. To ensure an equivalent start-up process, the same engine RPM trajectory, shown in Fig. 4, was maintained with the different constant lambda histories. This resulted in a reasonably similar Net-IMEP and COV during each start-up operation. It should be noted that spark timings were retarded to keep the same engine RPM trajectory with richer engine lambda conditions due to a more robust and stable combustion, allowing for additional spark retard from MBT. Consequently, the same history of inducted air mass was delivered to the cylinders, cycle by cycle, for all three different start-up processes.

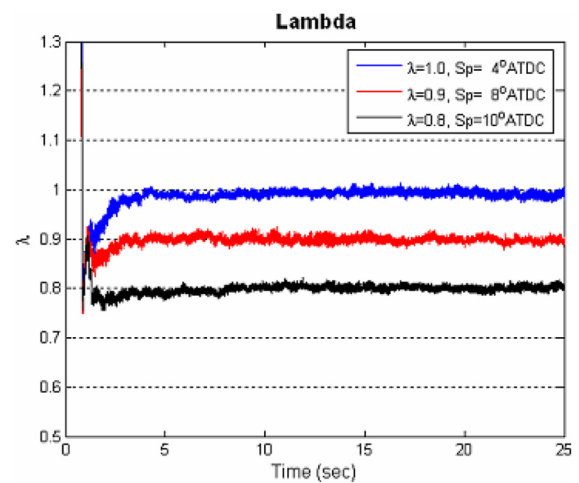


Figure 3. Lambda trajectories for three constant lambda start-up processes as a function of time after cranking.

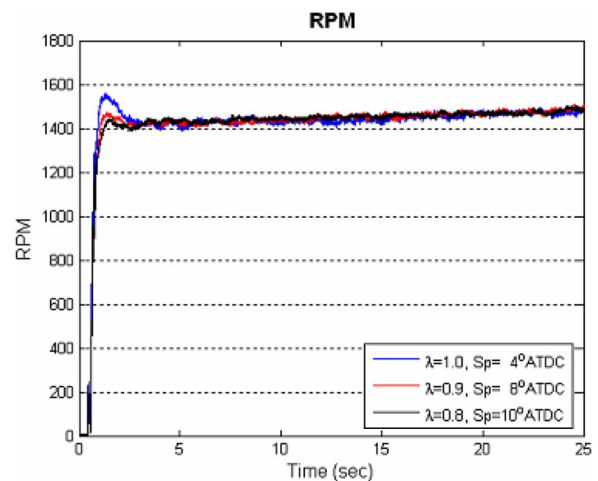


Figure 4. RPM trajectories for three constant lambda startup processes as a function of time after cranking.

The engine was calibrated to achieve the target operating condition for the park idle period, 2.0 bar Net-IMEP and 1450 RPM. The idle speed of these experiments was raised to 1450 RPM in order to provide a higher rate of thermal energy to the catalyst. All engine start-up experiments were conducted at approximately 20°C test-cell ambient conditions. The coolant temperature was initially fixed at 20°C by the external coolant control system. The test matrix, [Table 2](#), was designed for various secondary air injection flow rates and engine lambda conditions. The results of these tests are described and discussed in the following sections.

Table 2. Test matrix for the constant lambda start-up strategies with different levels of SAI

SAI λ_{engine}	3.63 (g/s)	7.26 (g/s)	10.89 (g/s)
0.8			
0.9			
1.0			
SAI / Intake Air	33%	67%	100%

QUENCHING EXPERIMENTS

Exhaust gas emissions at the cylinder exit were determined using exhaust quenching experiments, in order to assess the extent of HC, CO and H₂ oxidation within the exhaust port. Exhaust gas reactions were frozen by rapidly reducing exhaust gas temperatures at the exit plane of the exhaust valves with cold N₂. Experiments were performed using a fixed N₂ injection flow rate that was optimized for a stable and repeatable injection event. The amount of quenching gas was increased until cylinder-exit HC emissions were found to reach a plateau. Results from the quenching experiments provided exhaust gas emissions at the cylinder exit. These initial conditions and compositions were used to drive the exhaust plug flow heat transfer model, which is discussed in the following sections.

EXPERIMENTAL RESULTS AND DISCUSSION

ANALYSIS OF EXHAUST EMISSIONS

STEADY STATE EXPERIMENTAL RESULTS

Steady state cold-fluid testing was performed to understand the basic effects of secondary air injection on exhaust gas temperatures and emissions. The engine was operated with various spark timings at a fixed condition of 1200 rpm,

λ_{engine} = 0.9, and 8.0 g/s intake air flow to the engine. The experiments were repeated with secondary air and nitrogen injection at each operating condition. The physical cooling effects of secondary air were reasonably decoupled from the chemical heating effects by comparing nitrogen injection cases with air injection cases.

The exhaust gas temperatures were observed to increase with spark retard as shown in [Fig. 5](#). Phasing the combustion process later in the expansion stroke decreased the amount of useful work extracted from the burned gases, resulting in higher exhaust gas temperatures and increased post-flame oxidation rates.

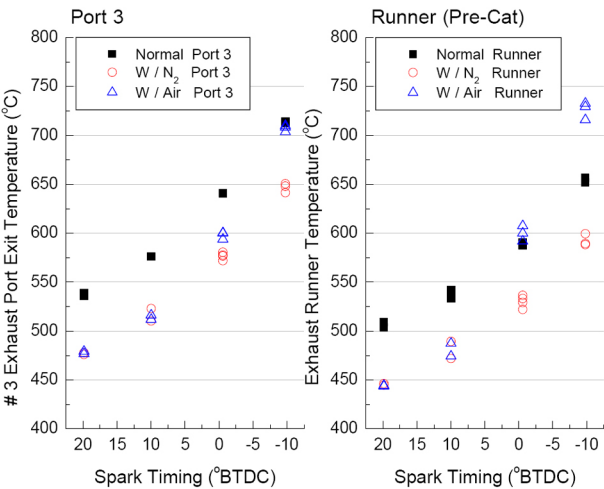


Figure 5. Exhaust gas temperatures at the port exit of cylinder no.3 and runner as a function of spark timing with the secondary air or nitrogen injection.

Higher exhaust gas temperatures from spark retard with secondary air promoted the thermal oxidation reaction prior to the catalyst and reduced the converter-in emissions as shown in [Fig. 6](#). This improvement in thermal oxidation also provided a higher rate of thermal energy to the catalyst. Therefore, it was concluded that spark retard was required in the engine start-up experiments with SAI in order to achieve faster light-off and lower converter-in emission during cold start.

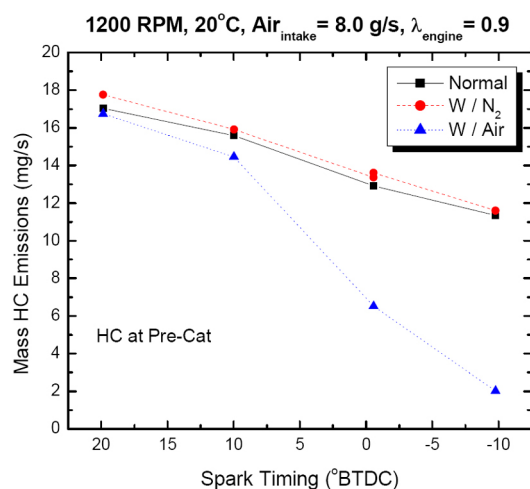


Figure 6. Hydrocarbon mass emissions at the pre-catalyst as a function of spark timing with the secondary air or nitrogen injection.

TRAPPED HC AND CONDENSED WATER IN CATALYST

HC storage and water condensation characteristics inside the catalytic converter were investigated to more precisely quantify mass emissions and thermal states of exhaust gas. The trapping of hydrocarbons is a property which most catalysts exhibit. Immediately after starting the engine, hydrocarbons (especially the heavier ones) adsorb onto the cold catalyst surface. This is known as the storage period. As the catalyst continues to heat up, but before light-off has been reached, the stored hydrocarbons desorb and then escape unoxidized. This is known as the release period. Figure 7 shows the amount of HC trapped in the catalyst with different secondary air injection rates. As the secondary air injection rate was increased, the amount of stored HC was decreased and the time for the storage and release period was also shortened considerably.

Due to the initially cold condition and the large surface area of the cells within the catalyst bricks, the exhaust gas temperature dropped significantly through the catalytic converter during cold start. A noticeable amount of water was also condensed inside the catalytic converter. It was found that quantification of condensed water inside the catalyst was required to precisely evaluate mass emissions and thermal states of exhaust gas due to the relatively low energy level of water at a given temperature. The amount of water condensed inside the catalytic converter, shown in Fig. 8, was calculated from the pre-catalyst and post-catalyst HC, CO and CO₂ concentrations and species balances which are described in more detail in [7]. The time period of water condensation and its evaporation was shortened noticeably as the secondary air injection rate was increased. Since the exhaust gas flow forced condensed water out from the tilted catalytic

converter, the amount of water condensed and evaporated did not add up to zero.

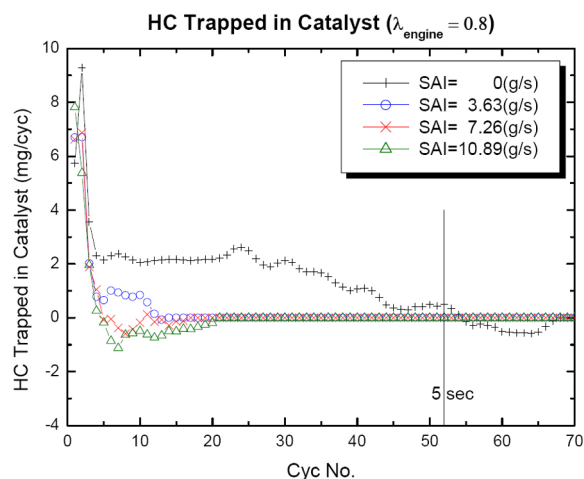


Figure 7. HC mass trapped inside the catalyst as a function of cycle number with different levels of SAI.

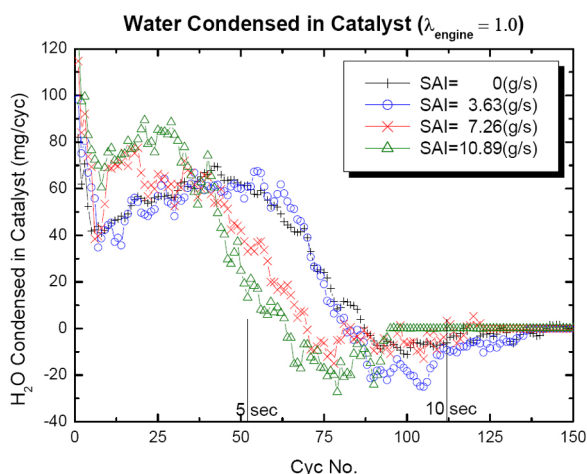


Figure 8. Water mass condensed inside the catalyst as a function of cycle number with different levels of SAI.

EFFECT OF SECONDARY AIR INJECTION LOCATION

A preliminary experiment was conducted to compare the effect of secondary air injection location on HC and CO emissions. Figure 9 shows two locations in the port, 5mm and 40mm from the exhaust valve seat, respectively. Figures 10 and 11 show the pre-catalyst and post-catalyst HC emissions with these two different air injection locations. The test clearly confirmed that injecting secondary air as close to the exhaust valve as possible was beneficial since the closer injection location strategy had the opportunity to enhance thermal oxidation of engine-out emissions, which further sped up catalyst light-off and reduced the converter-in and converter-out emissions. The profiles of CO emissions