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Analysis of Non-Selective Catalyst Reduction Performance with Dedicated Exhaust Gas Recirculation

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Abstract

Rich burn industrial natural gas engines offer best in class post catalyst emissions by using a non-selective catalyst reduction aftertreatment technology. However, they operate with reduced power density when compared to lean burn engines. Dedicated exhaust gas recirculation (EGR) offers a possible pathway for rich burn engines to use non-selective catalyst reduction aftertreatment technology without sacrificing power density. In order to achieve best in class post catalyst emissions, the precious metals and washcoat of a non-selective catalyst must be designed according to the expected exhaust composition of an engine. In this work, a rich burn industrial natural gas engine operating with dedicated EGR was paired with a commercially available non-selective catalyst. At rated brake mean effective pressure (BMEP) the air-fuel ratio was swept between rich and lean conditions to compare the catalyst reduction efficiency and post catalyst emissions of rich burn and dedicated EGR combustion. It was found that due to low oxides of nitrogen (NO_x) emissions across the entire air-fuel ratio range, dedicated EGR offers a much larger range of air-fuel ratios where low regulated emissions can be met. Low engine out NO_x also points towards a possibility of using an oxidation catalyst rather than a non-selective catalyst for dedicated EGR applications. The location of the NO_x-CO tradeoff was shifted to more rich conditions using dedicated EGR.

Keywords

Natural Gas Engine, Rich Burn, Dedicated Exhaust Gas Recirculation, Catalyst

1. Introduction

Rich burn natural gas engines play a necessary and prominent role in power generation for the oil and gas industry. The environmental protection agency (EPA) defines rich burn engines as any engine that is designed and operates at an air-fuel ratio of less than lambda 1.1 [1]. Because rich burn engines operate near stoichiometric conditions a three-way or also known as a non-selective catalyst can be used to reduce emissions of oxides of nitrogen (NO_x) and carbon monoxide (CO). A well-designed non-selective catalyst can achieve near 99% catalyst reduction efficiency of NO_x and CO when applied correctly to an engine [2]. However, the current tradeoff of rich burn natural gas engines is their limited power density due to high combustion temperatures that occur when operating at near stoichiometric conditions. Thus, consumers must decide between a natural gas engine that can achieve best in class post catalyst emissions, and a natural gas engine with increased power density such as a lean burn.

Exhaust gas recirculation has conventionally been implemented on engines in high-pressure or low-pressure loop configurations to limit the formation of NO_x. Dilution of the combustion charge using recirculated exhaust changes the thermodynamic properties of the combustion charge and effectively lowers peak combustion temperature which results in lower engine-out emissions of NO_x. High- and low-pressure loop EGR configurations rely on an EGR valve to meter the amount of exhaust recirculated back to the intake manifold at different engine operating conditions. A heat exchanger is used to reduce the temperature of the recirculated exhaust, but the EGR valve can often be exposed to gas temperatures in excess of 100˚C. Being exposed to this gas temperature for an extended period of time can limit the long-term reliability of an EGR valve. Some industrial natural gas engines are expected to operate at rated power nearly year-round, and because of this, long-term reliability of components is a critical design criterion.

Dedicated EGR is a variation of conventional high- and low-pressure loop configurations. The dedicated EGR method designates one or more engine cylinder(s) exhaust to be recirculated back to the intake manifold of the engine at all operating conditions. No EGR valve is used so the engine operates at a fixed effective EGR rate at all times. The impact that the recirculated exhaust gas has on combustion is controlled by changing the air-fuel ratio of the dedicated cylinder(s). Additional fuel is added to the dedicated cylinder(s) while the other cylinders remain at near stoichiometric conditions. A general schematic of dedicated EGR applied to a four-cylinder engine can be found in **Figure 1**. Fuel-rich combustion conditions produce partial oxidation combustion products such as hydrogen (H_2) and CO. At engine operating conditions where an effective lower EGR rate is necessary for acceptable engine performance, additional fuel is added to the dedicated cylinder(s). This results in fewer inert combustion product species of carbon dioxide (CO_2) and water (H_2O) and more species that have higher reactivity such as H_2 and CO.

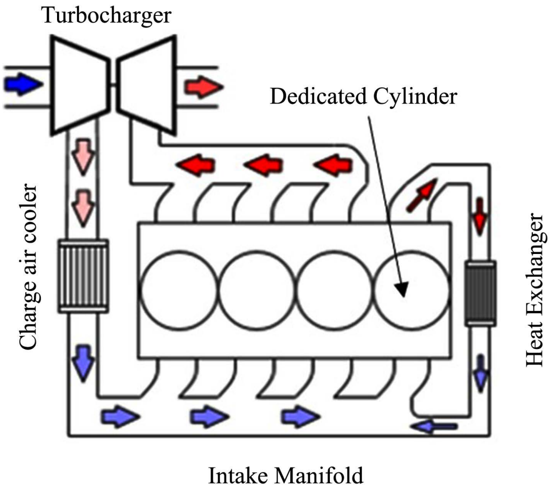

Figure 1. Four-cylinder engine outfitted with dedicated EGR on one engine cylinder.

If dedicated EGR is to be successfully implemented on an industrial natural gas engine an understanding of how a typical non-selective catalyst will perform when exposed to combustion products from a dedicated EGR engine. In this work, an industrial natural gas engine was reconfigured to operate with dedicated EGR, and a commercially available non-selective catalyst was installed on the engine.

Previous work in the area of hydrogen addition to exhaust gas recirculation focused on the effects of hydrogen addition to gasoline engine combustion, specifically reduction of engine knock and NO_x emissions [3] [4] [5]. Researchers at Southwest Research Institute were the first to introduce the concept of dedicated EGR. In publications by Alger *et al.* [6], the effects of hydrogen on EGR tolerance were examined and improvements in engine efficiency were noted. Further improvements in engine performance via increased compression ratio and higher boost pressure were shown by implementing dedicated EGR on gasoline-fueled engines [7] [8]. Extension of the lean limit was also observed by Liu *et al.* when partial oxidation combustion products of H_2 and CO were added to a single-cylinder engine operating on compressed methane gas [9].

2. Methods

The engine used for this work was a Caterpillar G3304 rich burn industrial natural gas engine. As a stock engine a G3304 engine is naturally aspirated with a 7.0 liter displacement and a low rated brake mean effective pressure (BMEP) of 6.7 bar at wide open throttle (WOT). The engine is spark ignited (SI) utilizing fine wire spark plugs as an ignition source. The quiescent combustion chamber is achieved through single intake and exhaust valves and a flat top piston design. Overall, the G3304 as a stock engine is a low technology engine utilizing a carburetor for air and fuel mixing, a fly-ball governor for engine speed control, and mechanical means of controlling spark timing. Operating the G3304 as a dedicated EGR engine required a number of changes to the engine design. The first was the addition of an engine control module (ECM). This allowed for electronic control of spark timing, closed loop air-fuel ratio control, and monitoring of numerous other engine operating conditions. The second was the addition of a simulated engine turbocharger. A turbocharger was simulated using a stand along supercharger and a back pressure valve. Another notable change made to the engine was that a port fuel injection system was added to the dedicated cylinder. This allowed the dedicated cylinder to operate at a different air-fuel ratio than the other three engine cylinders. Finally, based on previously published literature [10] an EGR mixer was added to the engine. Due to the expected intermittent pulses of exhaust coming from the dedicated cylinder a mixer was designed to dampen these pulses and allow for adequate mixing of dedicated cylinder exhaust and fresh air-fuel. **Table 1** shows general engine specifications for the G3304 engine used during this work. **Figure 2** shows a schematic for the

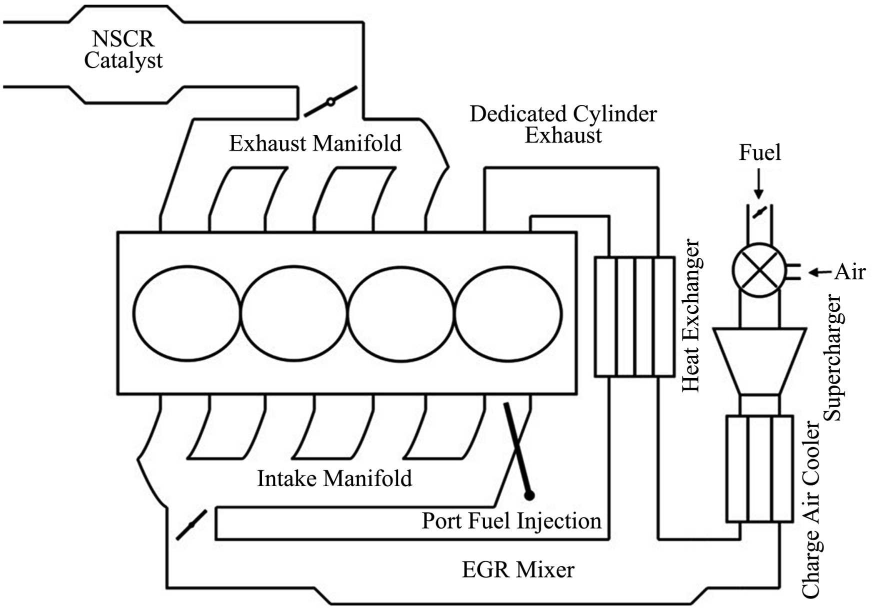

Figure 2. G3304 engine schematic while operating with dedicated EGR.

Table 1. Caterpillar G3304 rich burn industrial natural gas engine specifications.

Caterpillar G3304	
Number of Cylinders	4 (inline)
Rated Engine Speed	1800 rpm
Rated BMEP	6.7 bar
Compression Ratio	10.5
Displacement	7.0 L
Bore	120.7 mm
Stroke	152.4 mm
Piston/Head Design	Flat

engine while operating as a dedicated EGR engine. Key components on the engine are labeled. In this work, air-fuel ratio dithering to achieve improved catalyst efficiency was not implemented. However, the closed loop air-fuel ratio control used a PID control scheme in which the air-fuel ratio did oscillate slightly rich and lean about a chosen lambda. The magnitude and frequency of these oscillations were not modified at any time. The frequency of oscillations was 0.2 Hz and the magnitude of oscillations of lambda was 0.1.

One of the key considerations when modifying the G3304 engine to operate at a dedicated EGR engine was the mixing of fuel and air. A low-pressure fuel and air mixing system was built for the G3304 engine. As shown in **Figure 2** downstream of the fuel control valve, fuel and air were mixed in the stock carburetor for the G3304 engine. After this, the then mixed fuel and air passed through a supercharger and a charge air cooler before entering the EGR mixer. The general design of the EGR mixer is shown in **Figure 3**. The dedicated cylinder exhaust enters the mixer and is accumulated in a volume approximately 1.5 times that of the dedicated cylinder while the piston is at bottom dead center (BDC). The exhaust is entrained in the premixed fuel and air via orifices at various locations. The nature of this design ensured that the dedicated cylinder exhaust remained at a higher pressure than the incoming air and fuel under all operating conditions. Then the mixed fuel-air-exhaust exited the EGR mixer and passed over a butterfly valve used to control engine speed before finally entering the intake manifold of the engine. Together the carburetor, supercharger, charge air cooler, EGR mixer, and associated piping created a tortuous path for the air-fuel mixture and it was assumed that there was no stratification of gases.

The fuel supply for this natural gas engine was taken directly from a natural gas pipeline source. Gas composition was measured using a Varian CP4900 mini gas chromatograph. Methane number (MN) calculations were done using the MWM methane number method [11]. Lambda measurements were made using wide-band oxygen sensors placed upstream of the catalyst. Gaseous engine emissions were analyzed using two instruments. The first, a Rosemount five-gas rack measured CO, CO_2, total hydrocarbons (THC), oxygen (O_2), and oxides of nitrogen (NO_x). The second, an MKS Fourier transform infrared (FTIR) spectrometer was used to measure emissions such as species of volatile organic carbons (VOCs), nitric oxide (NO), and nitrogen dioxide (NO_2). A complete list of species quantified by the MKS FTIR is shown in **Table 2**. The FTIR method used to

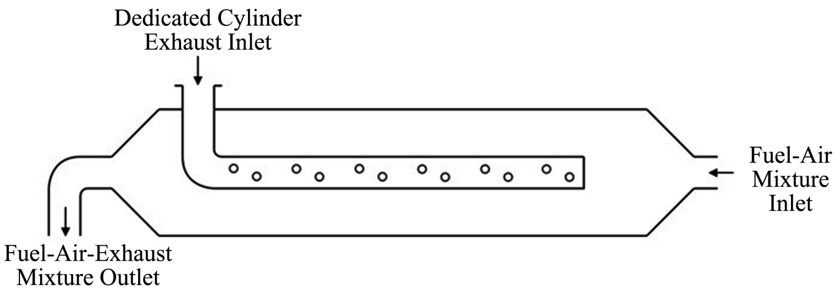

Figure 3. Dedicated EGR mixer schematic.

Table 2. Species quantified using FTIR.

FTIR Species Quantified
Carbon Monoxide (CO)
Carbon Dioxide (CO_2)
Nitric Oxide (NO)
Nitrogen Dioxide (N_2O)
Ammonia (NH_3)
Formaldehyde (CH_2O)
Methane (CH_4)
Ethane (C_2H_6)
Propane (C_3H_8)
Acetylene (C_2H_2)
Ethylene (C_2H_4)
Propylene (C_2H_6)
Water (H_2O)

analyze spectra was developed by MKS for exhaust species typically found in rich burn natural gas combustion. At selected engine operating points a third gaseous engine emissions measurement instrument, an Ecom J2KN Pro Series, was used. This portable emissions analyzer uses an electrochemical method to quantify species such as CO, NO, and NO_2. Each of these analyzers shared a common, heated sample line between the engine and the respective instruments. Gaseous emissions were sampled using averaging probes designed to collect gas from three different locations in the exhaust stream. The probes were placed upstream of the catalyst, downstream of the catalyst, and just downstream of the exhaust leaving the dedicated cylinder.

The catalyst used was designed and manufactured by DCL International. Given typical engine-out emissions from a rich burn natural gas engine, it was designed to reduce post catalyst emissions of CO and NO_x to 4 and 2 g/bhp-hr, respectively. The space velocity of the catalyst at the operating conditions tested in this work was approximately 30,000/hr, and the cell density was approximately 200 cells per square inch. Specific catalyst precious metals and wash coat composition were not available, but based on discussion with the catalyst manufacturer, typical non-selective catalyst reduction materials such as rhodium, platinum, palladium, cerium, and various promoters and stabilizers were used in this catalyst. The catalyst housing contains two substrates separated by a small volume. Exhaust gas temperature measurements were made at the inlet to the catalyst housing, between the substrates, and at the outlet of the catalyst housing.

Emissions data presented are representative of a 5-minute collection at a rate of 2 Hz, and unless otherwise noted the data was collected by the Rosemount

5-gas analyzer. Uncertainty shown in emissions figures comes from instrument linearity and calibration gas uncertainty and was calculated using the Kline and McClintock method [12]. Information about operation conditions of the engine while under test can be found in **Table 3**.

3. Results & Discussion

An initial evaluation of the catalyst performance was done by sweeping the air-fuel ratio of the engine while holding all other operating variables found in the "Baseline" column of **Table 3** constant. Based on observations made on previous engine tests on the G3304, it was theorized that the air-fuel ratio that would result in the best post catalyst emissions was lambda 0.990. Due to this observation lambda was incremented in very small steps (0.001) around that value and step size increased as lambda moved away from a value of 0.990. The largest step size taken was 0.005 lambda. Prior to doing the lambda sweep an initial evaluation of pre and post-catalyst engine emissions was done at 0.990 lambda. This test was repeated after the lambda sweep to ensure that no significant variation in engine performance had occurred over the course of the lambda sweep. **Figure 4** shows the post catalyst emissions of NO, CO, THC, and VOCs. Species considered VOCs here are propane, acetylene, ethylene, and propylene. The target emissions selected for this work were not to exceed 4.0 g/bhp-hr CO, 2.0 g/bhp-hr NO_x, and 0.7 g/bhp-hr VOCs post catalyst. Target emissions of CO and NO_x were set based on EPA CFR 40 Part 60 Subpart JJJJ for non-emergency SI natural gas and non-emergency SI lean-burn LPG engines with maximum engine power between 100 and 500 horsepower and manufactured prior to July 1st, 2008. The target VOC emission was based on the same EPA standard, engine type, and maximum power capability, but with a manufactured date prior to January 1st, 2011 [1].

The range of lambda values in which post catalyst CO emissions requirements are met is shown in the area shaded blue, and the range of lambda where post

Table 3. Engine operating conditions during the air-fuel ratio sweep.

Operating Conditions		
	Baseline	Dedicated EGR
BMEP (bar)	6.7	6.7
IMAT (˚C)	40	62
IMAP (psia)	11 - 13	17 - 18.5
Spark Timing (˚bTDC)	30	45
Spark Duration (μs)	150	365
Dedicated Cylinder Lambda	-	0.936
Glabal Lambda	Varied	Varied
MWM Methane Number	70 - 71	70 - 71

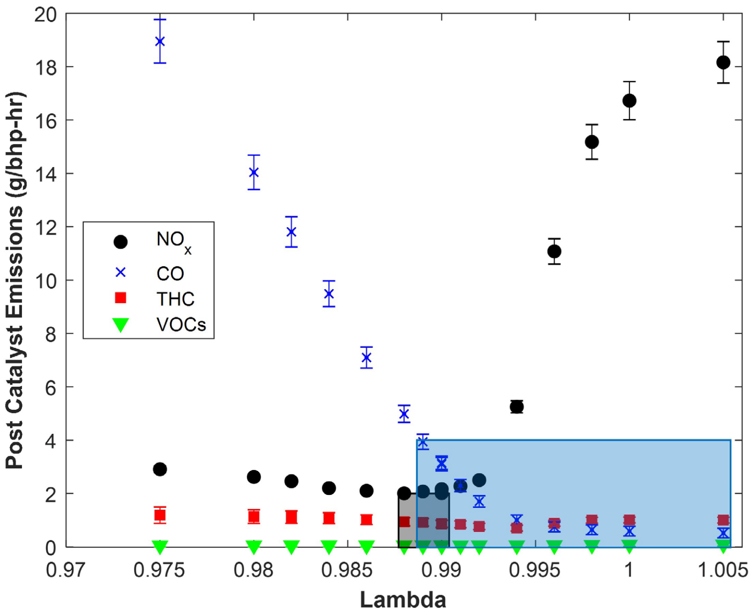

Figure 4. Rich burn baseline post catalyst emissions for the G3304 engine.

catalyst NO_x emissions requirements are met as shown in the area shaded black. The overlapping area is then the acceptable range of engine operation in terms of air-fuel ratio where post catalyst emissions targets are met. Post catalyst VOC emissions were less than 0.1 g/bhp-hr across the entire lambda sweep. Thus, the window of acceptable lambda for this engine-catalyst pair without dithering was small with a range only between 0.990 and 0.989 lambda.

Examination of catalyst efficiency as a function of lambda shows how the catalyst performed across the range of lambda values tested. On a fundamental level, a catalyst simply provides area for gaseous molecules to meet, react with other molecules, and ultimately shift the composition of the gas towards equilibrium concentrations. The precious metals included in a wash coat provide reaction pathways for emissions such as NO and CO to come to equilibrium with a lower activation energy and at an increased rate. However, a non-selective catalyst such as the one used in this work must be designed such that the catalyst area or in another sense the number of sites available for reaction is adequate for the concentration of species passing through the catalyst. This measure is quantified in space velocity and as mentioned was approximately 30,000/hr for the catalyst and engine. Per discussion with the manufacturer of this catalyst, a space velocity of 30,000/hr was well within the acceptable range that would result in good performance. Of specific note in any catalyst reduction efficiency study is the NO_x-CO tradeoff. The results shown in **Figure 5** demonstrate the nonlinear response that NO_x and CO have at only slightly fuel-rich conditions between 0.990 and 0.995 lambda. At conditions rich in this range a high catalyst reduction of NO_x is shown. Examination of FTIR results in which a distinction between NO and NO_2 was made shows that across the entire range of lambda values NO was by far the primary constituent in the NO_x measurement. The highest NO_2

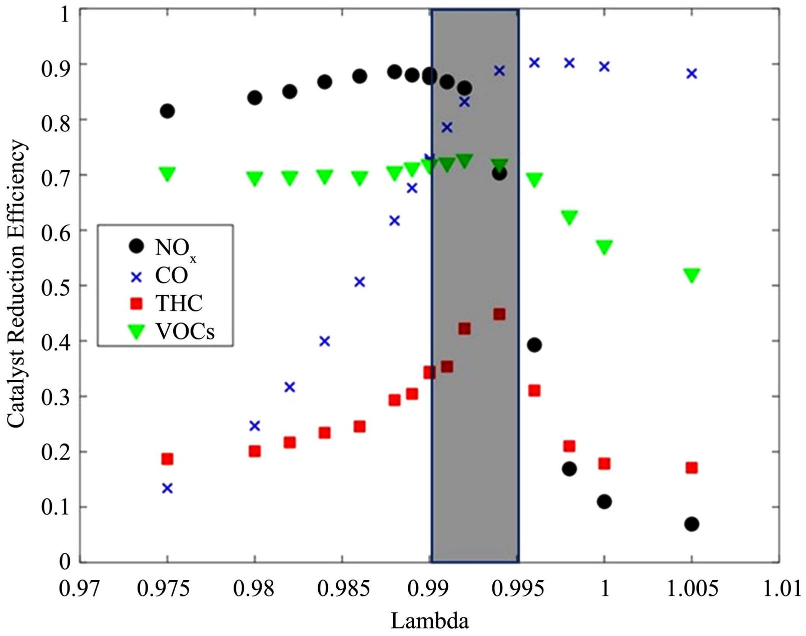

Figure 5. Catalyst reduction efficiency as a function of rich burn engine air-fuel ratio. The range of optimal catalyst performance is shown in the area marked in grey (0.990 - 0.995 lambda.

concentration measured in this lambda sweep was a concentration of 10 ppm while the pre-catalyst NO values ranged from 2500 - 3000 ppm. Break down of NO in a 3-way catalyst is done primarily by reactions taking place with the precious metal rhodium where nitrogen and oxygen atoms are separated and attached to different sites. Monatomic nitrogen is able to move freely on the catalyst surface, recombine with other monatomic nitrogen and leave the catalyst. However, conditions in the catalyst are not sufficient for oxygen to be removed in this way. The presence of CO in the exhaust allows for oxygen to be liberated from the catalyst surface, and at rich engine operating conditions, CO is abundant. Thus, in rich conditions a high catalyst reduction efficiency of NO is possible. Similarly, in rich conditions a low catalyst reduction efficiency of CO is seen due to the high concentration of CO and the lack of available oxygen to oxidize CO to CO_2.

At conditions lean of the 0.990 - 0.995 lambda range catalyst reduction efficiency of CO is high due to the increased availability of oxygen in the exhaust that can be used to oxidize CO. Due to the limited number of reaction sites available on a catalyst surface, at lean conditions where there is excess O_2 catalyst reduction efficiency of NO_x is low because of a competition for sites that takes place between these two species. It follows that if reaction sites on the catalyst are occupied by O_2 molecules the NO_x molecules are not able to be destroyed. When designed properly, non-selective catalysts are capable of achieving 98% - 99% reduction efficiency for NO_x and CO. Examining the catalyst performance in this work reveals that in the range of optimal performance for both NO_x and CO conversion the best reduction efficiency achieved was 86% and 83% for NO_x

and CO, respectively. High reduction efficiency not only necessitates a well-designed catalyst but also careful management of oxygen within the catalyst. Decreased reduction efficiency in this work is likely a product of variations in cylinder to cylinder combustion and lack of tuned air-fuel ratio dithering. The performance of catalyst VOC reduction efficiency at conditions lean of approximately 0.995 lambda was unexpected. The expected result was that VOC reduction efficiency would trend similarly to CO reduction efficiency, but **Figure 5** shows that as conditions became more lean VOC reduction efficiency decreased. This behavior can likely be attributed to the combination of precious metals present in the catalyst not being correct for this particular exhaust composition. Pre-catalyst concentrations of formaldehyde ranged from less than 1 ppm to approximately 10 ppm. Post-catalyst measurement showed only trace amounts of formaldehyde which suggested that it was successfully oxidized in the catalyst.

Following the baseline, air-fuel ratio sweep the G3304 engine was reconfigured to operate with dedicated EGR. Engine operating conditions for dedicated EGR listed in **Table 3** were shown via a response surface method optimization to be the best-operating conditions for the G3304 engine with dedicated EGR. Engine BMEP of 6.7 bar was held constant between the baseline and dedicated EGR tests while intake manifold pressure (IMAP) was varied to achieve the same engine BMEP. Natural gas fuel composition varied only slightly between 70 and 71 MWM methane number and fuel concentrations of methane, ethane, and propane remained near 83%, 11%, and 2%, respectively. The specific fuel concentrations were very similar to the baseline engine operating fuel concentrations. Prior to performing the dedicated EGR air-fuel ratio sweep it was observed in other tests that the engine air-fuel ratio that resulted in a pre-catalyst CO to NO_x ratio of 2:1 was approximately 0.996 lambda. This air-fuel ratio was chosen as the "center" of the dedicated EGR air-fuel ratio sweep. Four repeated tests at this air-fuel ratio were done during the sweep shown in **Figure 6**. Similar to the

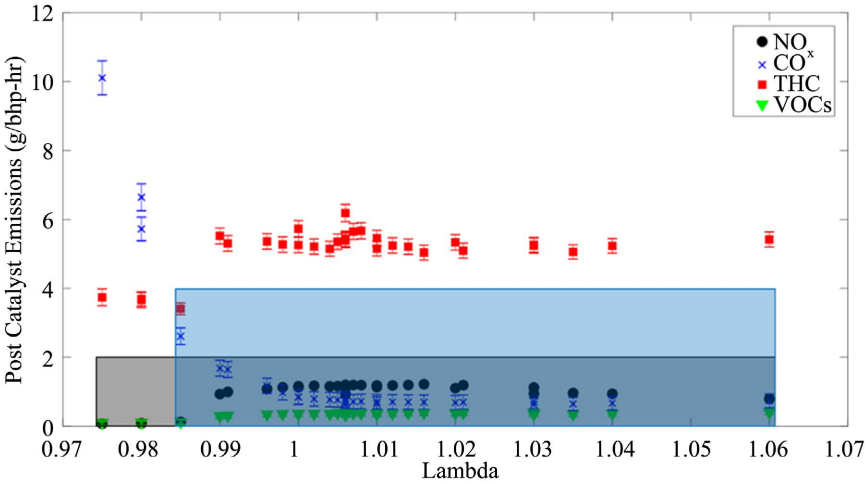

Figure 6. Post catalyst emissions as a function of air-fuel ratio. The engine was operating with dedicated EGR. The dedicated cylinder was held at a constant air-fuel ratio of 0.936 lambda while the three remaining cylinders' air-fuel ratio was adjusted.

baseline air-fuel ratio sweep small steps in lambda were taken around the center point with the steps between test points getting larger further away from lambda 0.996. Operating the G3304 engine with dedicated EGR results in large differences in the acceptable range of air-fuel ratio when compared to operating as a conventional rich burn engine. The range of acceptable air-fuel ratio where CO emissions are less than 4.0 g/bhp-hr, NO_x emissions are less than 2.0 g/bhp-hr, and VOC emissions are less than 0.7 g/bhp-hr is between 0.985 and 1.06 lambda. Theoretically, this range could be even larger as an upper limit on lambda was not found within the scope of this study. The means by which this range was achievable was clearly due to low NO_x emissions. The highest post-catalyst NO_x emissions of 1.21 g/bhp-hr found were at an air-fuel ratio of lambda 1.016. This was approximately 16 times lower than the highest post-catalyst NO_x emissions found in the baseline air-fuel ratio sweep. A notable decrease in NO_x emissions was expected due to the impact that exhaust gas recirculation, in general, has on peak combustion temperatures during a combustion event. Near stoichiometric conditions the Zelovich mechanism, which is a strong function of temperature, accounts for the majority of NO and NO_2 production, and it follows that when peak combustion temperatures are lowered engine-out NO_x emissions decrease. Another notable difference between the baseline and dedicated EGR post-catalyst emissions was the high unburned hydrocarbon emissions found in the dedicated EGR tests. This can be explained by incomplete combustion of methane and ethane fuel while operating with dedicated EGR. Pre-catalyst baseline exhaust concentrations of methane and ethane were on the order of 300 and 30 ppm, respectively with low catalyst reduction efficiency near 20%. Pre-catalyst methane and ethane dedicated EGR emissions were on the order of 1500 and 150 ppm, respectively with very low catalyst reduction efficiency near 10%. While possible, oxidation of methane in a catalyst is much more difficult than in other hydrocarbons because breaking the first C-H bond takes roughly 40 kJ/mol more energy than the subsequent bonds, much more than in other hydrocarbons [13]. It is clear that conditions in the catalyst while operating with exhaust coming from the dedicated EGR configuration were not adequate to allow significant oxidation of methane and ethane to take place. As methane is now recognized as a major greenhouse gas [14], this result is not desirable. However, as outlined in previous work by the author [15] [16] there is ample opportunity to improve combustion efficiency of natural gas dedicated EGR engines that would result in lower engine-out hydrocarbon emissions of methane and ethane.

Figure 7 shows the catalyst reduction efficiency for the G3304 engine while operating with dedicated EGR. Catalyst reduction efficiency of the G3304 engine operating with dedicated EGR had similar general trends to the baseline reduction efficiency for CO, THC, and VOCs. The air-fuel ratio where the NO_x-CO tradeoff occurred, 0.985 lambda, was slightly more rich conditions than the baseline air-fuel ratio which occurred at 0.992 lambda. At conditions, richer of 0.985 lambda catalyst reduction efficiency of NO_x and VOCs was between 80% - 90% while the reduction efficiency of CO changed drastically from less

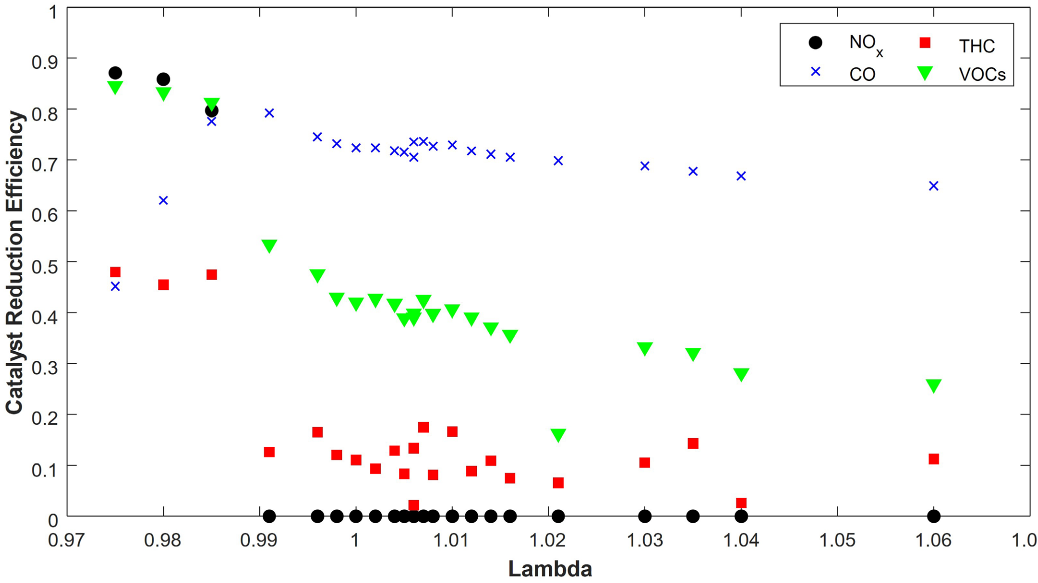

Figure 7. Dedicated EGR catalyst reducation efficiency as a function of lambda.

than 50% at the most rich conditions of 0.970 lambda to nearly 80% at lambda 0.985. At all conditions more lean than 0.985 lambda, **Figure 7** shows a catalyst NO_x efficiency of 0. Data collected in this range showed an increase in NO across the catalyst. This result was confirmed by all three measurement methods described previously in the "Methods" section of this work. Taking the uncertainty of the measurement methods and the uncertainty associated with the standard deviation of the repeated "center" points the result did prove to be statistically significant. Using Chemkin 19.2 Equilibrium model and the known combustion charge composition a study was done to find the expected equilibrium NO concentration in the post combustion gases. This study revealed that at all air-fuel ratios the calculated equilibrium concentration of NO was higher than that of the measured engine out concentration. If a catalyst simply accelerates and allows for chemical equilibrium to be achieved then theoretically an increase in NO emissions is possible. However, without a clear explanation as to how this can occur in a non-selective catalyst at lean conditions these results were normalized to a catalyst efficiency of 0. The notable result from this figure is that the best operating conditions in terms of catalyst reduction efficiency for a natural gas engine using dedicated EGR appear to be rich conditions near 0.985 lambda.

A direct comparison of post catalyst baseline and dedicated EGR NO_x, CO, THC, and VOC emissions is shown in **Figure 8**. Quite clearly it can be shown the impact of natural gas dedicated EGR combustion when paired with a common non-selective catalyst. In the subfigure of the upper left it is evident that post catalyst emissions on NO_x remain low over a wide range of air-fuel ratios. In fact, the pre-catalyst NO_x values are similar to that of post-catalyst dedicated EGR results which means that in order to meet a 2.0 g/bhp-hr limit of NO_x a catalyst would not be needed. This opens up the possibility to use an oxidation

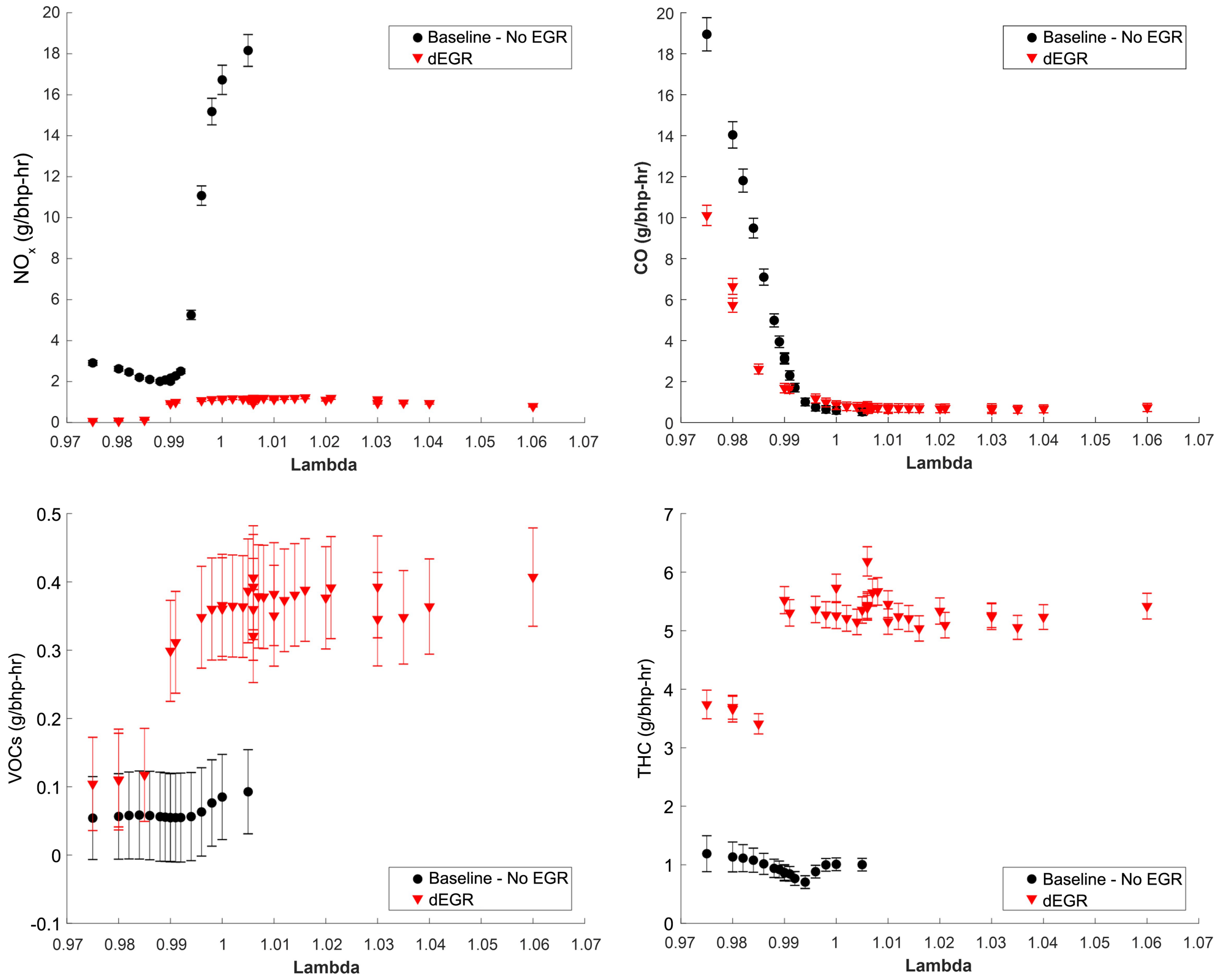

Figure 8. Post catalyst emissions of No_x, CO, THC, and VOCs as a function of lambda. Dedicated EGR results are shown in red and rich burn baseline results are shown in black.

catalyst rather than a non-selective catalyst on dedicated EGR engines. Examining the subfigure of the upper right it is seen that at rich conditions post catalyst dedicated EGR emissions of CO are lower than that of the baseline engine operation. This is primarily due to the increased availability of oxygen in the pre and post catalyst exhaust of dedicated EGR tests. Even in the most fuel-rich dedicated EGR conditions at least 0.50% oxygen was available in the pre-catalyst exhaust. This available oxygen allowed for high concentrations on the order of ~5000 ppm to be oxidized in the catalyst while operating with dedicated EGR. The available oxygen content in dedicated EGR exhaust may be a function of poor combustion efficiency and thus would not be advantageous for the overall operation of the engine. Certainly, a dedicated EGR operating condition that has an air-fuel ratio lean of 0.985 lambda could be chosen to meet CO emissions requirements. The two lower subfigures of Figure 8 depict a comparison of dedicated EGR and rich burn post catalyst VOC and THC emissions. Unburned hydrocarbon emissions found in premixed combustion are produced mainly by physical means within a combustion chamber. That is, they are protected from burning by the cold wall effects in crevice volumes, absorbed and desorbed in engine oil, etc. [17]. **Figure 5** and **Figure 7** show that the catalyst reduction efficiency of VOCs and THC emissions was higher while the engine was operating at baseline conditions. This increased reduction efficiency paired with a higher engine out THC and VOC emissions from the dedicated EGR configuration lead to the result shown in the lower two subfigures of **Figure 8**.

The final consideration given when comparing catalyst performance was an analysis of the exhaust temperature at the catalyst inlet, between the two catalyst substrates, and at the catalyst outlet. **Figure 9** shows the catalyst temperatures for baseline and dedicated EGR as a function of air-fuel ratio lambda. At each temperature measurement location the dedicated EGR configuration results in catalyst temperatures that are between 100˚C and 150˚C higher than baseline conditions. Per the catalyst manufacturer specifications, temperatures in that catalyst should not exceed approximately 730˚C to ensure designed catalyst life. The three richest conditions tested using dedicated EGR resulted in catalyst temperatures in excess of this specified upper limit. Temperatures at these three test cases were slightly higher than 750˚C. The presence of increased levels of VOCs and THC in dedicated EGR tests and associated oxidation of hydrocarbons likely contributed to the higher catalyst temperatures observed. Based on these results design of a catalyst to be used with dedicated EGR would need to include a consideration of using materials were greater tolerance for high temperatures. However, if combustion performance in a dedicated EGR engine were to be improved it is likely that lower catalyst temperatures would be observed.

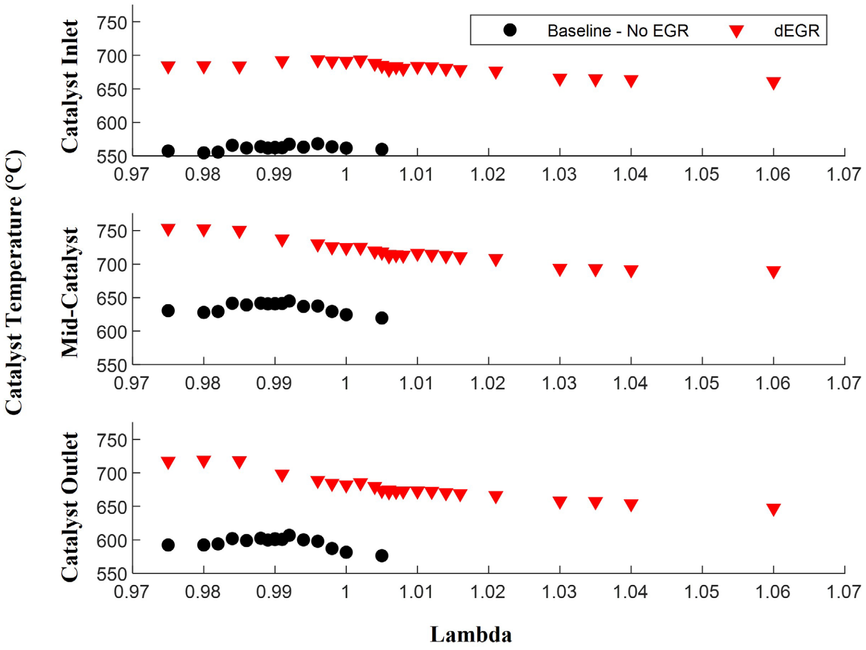

Figure 9. Exhaust gas temperature at the catalyst inlet, between catalyst substrates, and at the catalyst outlet as a function of lambda.

4. Conclusion

A rich burn industrial natural gas engine was modified to operate with dedicated exhaust gas recirculation. A commercially available non-selective catalyst was paired with the engine to understand how catalyst reduction efficiency and post catalyst emissions would be affected by operating an engine with dedicated EGR. While holding all other conditions constant an air-fuel ratio sweep was carried out on the engine operating as stock rich burn and with dedicated EGR. The following conclusions can be made based on the results of this work.

- Based on post catalyst emissions, the range of air-fuel ratio in which emissions criteria were met was increased from 0.001 lambda while operating as a rich burn engine to 0.075 lambda while operating with dedicated EGR. This was due to the low post catalyst NO_x emissions across the entire lambda sweep.
- Across the entire dedicated EGR lambda sweep (0.970 - 1.06) pre-catalyst NO_x emissions remained below 1.3 g/bhp-hr. This was below the target of 2.0 g/bhp-hr and suggests that only an oxidation catalyst may be necessary for dedicated EGR engine to meet low emissions requirements.
- The location of the NO_x-CO tradeoff was shifted from approximately 0.992 lambda at baseline conditions to approximately 0.985 lambda using dedicated EGR.
- Dedicated EGR catalyst temperatures remained higher at all air-fuel ratios. Catalyst materials suited to exposure to higher temperatures should be considered while operating and engine with dedicated EGR.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] EPA CFR 40 Part 60 Subpart JJJJ. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-JJJJ

[2] DCL International. Catalyst Specifications. https://www.dcl-inc.com/catalyst-specifications/#three-way-catalysts

[3] Ivanic, Z., Ayala, F., Goldwitz, J. and Heywood, J.B. (2005) Effects of Hydrogen Enhancement on Efficiency and NO_x Emissions of Lean and EGR-Diluted Mixtures in a SI Engine. SAE Paper 2005-01-0253. https://doi.org/10.4271/2005-01-0253

[4] Jamal, Y., Wagner, T. and Wyszynski, M.L. (1996) Exhaust Gas Reforming of Gasoline at Moderate Temperatures. *International Journal of Hydrogen Energy*, **21**, 507-519. https://doi.org/10.1016/0360-3199(95)00103-4

[5] Gerty, M.D. and Heywood, J.B. (2006) An Investigation of Gasoline Engine Knock Limited Performance and the Effects of Hydrogen Enhancement. SAE Paper 2006-01-0228. https://doi.org/10.4271/2006-01-0228

[6] Alger, T., Gingrich, J. and Mangold, B. (2007) The Effect of Hydrogen Enrichment on EGR Tolerance in Spark Ignited Engines. SAE Paper 2007-01-0475.

https://doi.org/10.4271/2007-01-0475

[7] Alger, T. and Mangold, B. (2009) Dedicated EGR: A New Concept in High Efficiency Engines. SAE Paper 2009-01-0694. https://doi.org/10.4271/2009-01-0694

[8] Alger, T., Mangold, B., Roberts, C. and Gingrich, J. (2012) The Interaction of Fuel Anti-Knock Index and Cooled EGR on Engine Performance and Efficiency. SAE Paper 2012-01-1149. https://doi.org/10.4271/2012-01-1149

[9] Liu, C., Li, F., Song, H. and Wang, Z. (2018) Effects of H_2/CO Addition on Knock Tendency and Lean Limit in a Natural Gas SI Engine. *Fuel*, **233**, 582-591. https://doi.org/10.1016/j.fuel.2018.06.102

[10] Denton, B., Chadwell, C., Gukelberger, R. and Alger, T. (2017) Design and Implementation of a D-EGR Mixer for Improved Dilution and Reformate Distribution. SAE Paper 2017-01-0647.

[11] EUROMOT. MWM Methane Number Calculator. https://www.euromot.eu/publication-and-events/publications

[12] Kline, S.J. and McClinktock, F.A. (1953) Uncertainties in Single Sample Experiments. *Mechanical Engineering*, **75**, 3-8.

[13] Glassman, I. and Yetter, R.A. (2008) Combustion. Academic Press, Cambridge.

[14] Methane: The Other Important Greenhouse Gas. EDF. https://www.edf.org/climate/methane-other-important-greenhouse-gas

[15] Van Roekel, C., Montgomery, D.T., Singh, J. and Olsen, D.B. (2019) Evaluating Dedicated Exhaust Gas Recirculation on a Stoichiometric Industrial Natural Gas Engine. *International Journal of Engine Research*, **22**, 491-502. https://doi.org/10.1177/1468087419864733

[16] Van Roekel, C., Montgomery, D.T., Singh, J. and Olsen, D.B. (2021) Response Surface Method Optimization of a Natural Gas Engine with Dedicated Exhaust Gas Recirculation. *International Journal of Engine Research*, **23**, 577-590.

[17] Heywood, J.B. (1988) Internal Combustion Engine Fundamentals. McGraw-Hill, New York.

Nomenclature

BMEP—brake mean effective pressure

NO_x—oxides of nitrogen

CO—carbon monoxide

EGR—Exhaust gas recirculation

Lambda—ratio of an engines actual air-fuel ratio to a stoichiometric air-fuel ratio

VOCs—volatile organic carbons

THC—total hydrocarbons

IMAP—intake manifold pressure

Catalyst Reduction Efficiency—ratio of pre-catalyst emissions to post catalyst emissions