

Development of a Catalytic Exhaust System for a Direct-Injection Two-Stroke Cycle Engine

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ABSTRACT

During the late 90's, the US government announced plans to phase out the use of snowmobiles in Yellowstone National Park due to environmental concerns. Prior to this decision, the snowmobile marketplace was dominated by snowmobiles equipped with two-stroke engines due to their high power to weight ratio. However, shortly after the government ruling the major snowmobile manufacturers began adding 4-stroke touring snowmobiles to their model lineups and began development of direct-injection two-stroke engines suited for snowmobile applications. With this in mind, the University of Idaho Clean Snowmobile Team has chosen to design, build, and test a snowmobile equipped with a gasoline direct-injection (GDI) two-stroke engine that maintains the performance of a traditional two-stroke engine while providing significant emission reductions and fuel consumption gains. To further emission improvements, an exhaust catalyst is to be added. This project is a review of literature on the development of exhaust catalysts and determines the optimal characteristics for a GDI two-stroke snowmobile catalyst.

INTRODUCTION

The pressure has been increasing of late for off-road vehicle manufacturers to reduce the exhaust emissions of their vehicles. In response to this pressure, the Society of Automotive Engineers (SAE) has sponsored a student competition to develop cleaner and quieter snowmobiles. The Clean Snowmobile Competition (CSC) encourages students to produce viable solutions that reduce both emission and noise production while maintaining the performance characteristics of a stock touring snowmobile. For the 2003 competition, the University of Idaho Clean Snowmobile Team is developing a GDI two-stroke powered snowmobile. The innate emission characteristics of a GDI two stroke are alone significantly better than that of a traditional two-stroke; however, to be competitive in the competition, the team has decided to also incorporate an exhaust catalyst for further emission reductions. The primary

areas of focus for this paper are type of catalyst, catalyst shape and construction, and the scavenging inefficiencies resulting from increased backpressure in the exhaust system.

Spark-ignited (SI) engine emissions are generally represented in four categories, unburned hydrocarbons (UHC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter. Due to the purity of modern fuels, particulate matter is not a major contributor to SI engine emissions and will not be looked at here. UHC's are the result of incomplete combustion, primarily caused by an overly rich combustion mixture. In addition to rich combustion, UHC's can also result from poor fuel atomization and flame quenching. CO emissions typically mirror UHC emission in that a leaner mixture results in lower CO levels. NO_x follow an opposite trend in which the higher combustion temperatures found with slightly lean operation increase the NO_x levels in the exhaust [2]. For the purpose of the CSC catalyst development, the inverse relation between NO_x emissions and UHC and CO emissions will be addressed by assuming a slightly rich combustion condition to reduce NO_x production and the incorporation of an exhaust catalyst to reduce the UHC and CO emissions resulting from the rich combustion. This assumption can be further justified by the fact that two-stroke engines have inherently low NO_x emissions due to scavenging inefficiencies [1].

GDI ENGINE CHARACTERISTICS

The GDI engine incorporated into the University of Idaho CSC entry will be a high-pressure direct injection (HPDI) system. This system uses a high-pressure fuel pump to deliver fuel to electronically controlled injectors. The fuel is then injected directly into the combustion chamber after the exhaust port has closed. This eliminates the fuel short-circuiting that is found in conventional two-stroke engines, therefore greatly improving the emissions. An alternative to the HPDI system, the air assisted GDI system, can actually reduce HC emissions to levels lower than port-injected four-stroke engines. In

an air assisted GDI system the fuel is injected with the assistance of a high-pressure air blast. This system has the ability to operate in highly stratified conditions at very lean air/fuel ratios, which can reduce HC emissions significantly [3]. The HPDI system is not capable of running this lean and will actually most likely be run slightly rich to preserve power and ensure thermal stability. Therefore, the expected HC emissions will be similar or slightly higher than a four-stroke SI engine.

HPDI ENGINE EMISIONS

In selecting a catalyst, one must identify the exhaust gas species of interest and establish criteria for which the benefits of different catalysts will be evaluated. The objective of this project is to select a catalyst that will provide the emission reductions that result in the highest possible score at the 2003 CSC competition. Evaluation of the competition scoring criteria shows that the scoring is based upon CO and UHC + NOx. The scoring function is shown in Eq. (1).

$$\text{YourScore} = 100 + 133 * \left(\frac{(\text{HC} + \text{NOx})_{\text{ref}} - (\text{HC} + \text{NOx})_{\text{your}}}{(\text{HC} + \text{NOx})_{\text{ref}} - (\text{HC} + \text{NOx})_{\text{min}}} \right) + 67 * \left(\frac{\text{CO}_{\text{ref}} - \text{CO}_{\text{your}}}{\text{CO}_{\text{ref}} - \text{CO}_{\text{min}}} \right) \quad (1)$$

Therefore, the goal of the catalyst is to minimize CO and the sum of HC and NOx.

Shown in figure 1 are the untreated, wide open throttle, emissions data for UHC, NOx, and CO in a GDI two-stroke cycle engine and a port injected two-stroke cycle engine as documented by Kenny [4]. The GDI engine tested here was not using a HPDI system but instead was fitted with an air-assisted GDI fuel delivery system. However, the engine was operated at the leanest mixture and minimum ignition advance for maximum torque [4], which indicates that the mixture was slightly rich and therefore similar to the CSC engine. This data illustrates the engine out emissions that one would expect from a GDI two-stroke engine and verifies the previous assumption that the UHC, CO and NOx emissions are comparable or lower than that of a four-stroke cycle engine.

Since NOx are already assumed to be low due to the two-stroke cycle and slightly rich combustion, their reduction is the least important and the oxidation of HC and CO is the primary goal of the catalyst.

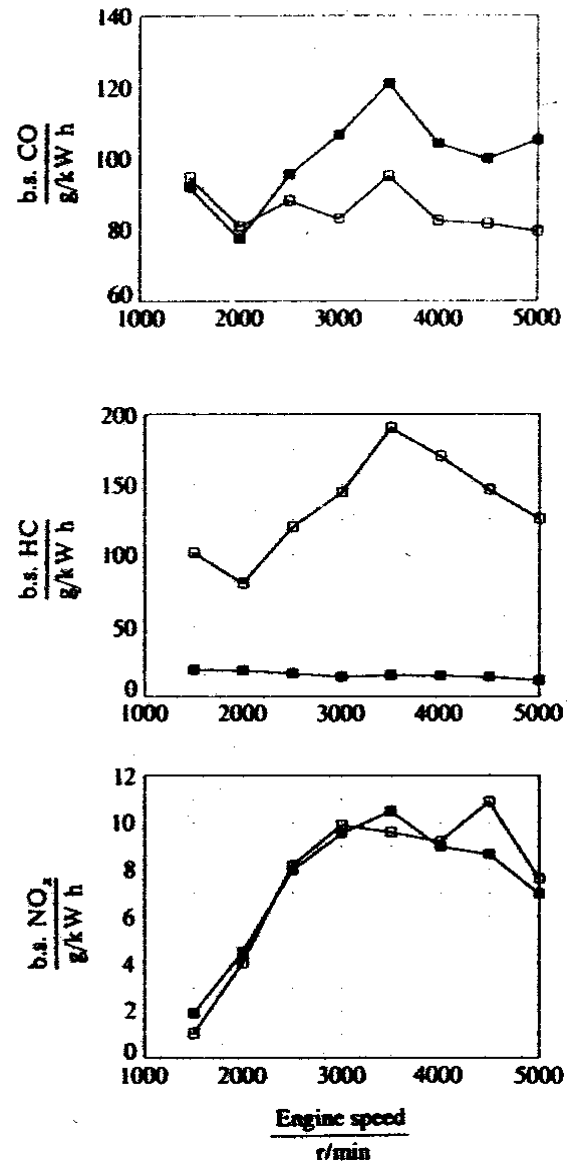


Figure 1: Comparison of inlet EFI and air-assisted direct injection in the 270 cm³ QUB cross-scavenged engine at WOT [4].

CATALYSTS

Catalysts rely on three different mechanisms to accomplish their task, UHC oxidation, CO oxidation, and NOx reduction. The two oxidation reactions rely upon the presence of excess oxygen in the exhaust stream to complete the reactions. Under rich operation this can pose a problem since all of the oxygen is combusted. One solution is to add an external air pump that feeds fresh air into the exhaust stream. This measure should

not be needed for a GDI two-stroke due to the short-circuiting of fresh air during the scavenging process.

UHC OXIDATION

The UHC oxidation mechanism begins with the absorption of UHC and O_2 onto the surface of the catalyst. The O_2 reacts with the catalyst to form two oxygen radicals, which in turn react with the UHC to form H_2O and CO . The H_2O is released into the exhaust stream and the CO is held by the catalyst until it reacts with the oxygen radicals to form CO_2 [2].

CO OXIDATION

The CO oxidation occurs in the same manner as the UHC oxidation. The CO is absorbed into the catalyst and reacts with oxygen radicals to form CO_2 , which is then desorbed into the exhaust stream [2].

NOX REDUCTION

The NOx reduction mechanism performs in a slightly different manner than that of the UHC and CO oxidations. Instead of consuming the excess oxygen in the exhaust, it actually creates excess oxygen. The NOx is absorbed by the catalyst and upon contact with the washcoat, it is separated into nitrogen and oxygen radicals. The nitrogen radicals then combine to form N_2 and the oxygen radicals are left to react with the UHC and CO to form CO_2 and H_2O [2].

CATALYST TYPES

There are three main types of catalysts used for SI engine exhaust after-treatment, these are oxidation catalysts, dual-catalysts, and three-way catalysts with the later being the most advanced.

Oxidation Catalysts

Oxidation catalysts perform the operation of reducing UHC and CO but have no effect on NOx emissions. This is due to the fact that they only employ the two-oxidation mechanisms. Since they rely purely on the oxidation reactions, typically a secondary air pump is added to the exhaust system to ensure that there is an adequate supply of oxygen in the exhaust stream. To control NOx emissions, oxidation catalysts are usually used in systems that already have NOx controlling systems in place, such as exhaust gas recirculation (EGR) and delayed ignition timings [1].

Dual Catalysts

Dual catalysts control UHC, CO, and NOx without the need for EGR or retarded ignition timings. The first catalyst in the system is a NOx reduction catalyst that decomposes the NOx to N_2 and oxygen radicals. For this process to occur efficiently, it is necessary for the engine to be running in a slightly rich condition at all times. This precise control of the air/fuel ratio typically

requires the use of an oxygen sensor to provide feedback to the ECU. The second catalyst in the dual catalyst system is an oxidation catalyst that performs the oxidation reactions of the UHC and CO. One problem that is encountered in the use of dual catalyst systems is that the rich combustion condition needed for the NOx reduction mechanism to function efficiently does not provide adequate excess oxygen to the oxidation catalyst. The NOx reduction reaction itself does supply a few oxygen radicals but typically secondary air injection is added between the two catalysts to ensure the oxidation reactions are driven to completion [1].

Three-way catalysts

Three-way catalysts are the most commonly used catalyst in the automotive industry today. They incorporate many of the same concepts as a dual catalyst but accomplish the task within a single catalyst. Figure 2 illustrates the lay out of a typical three-way catalyst.

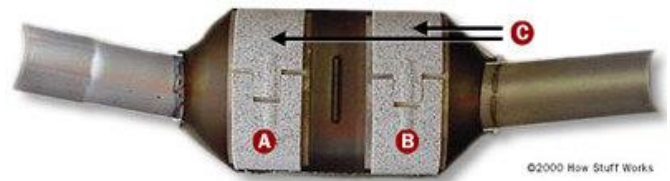


Figure 2: Typical Three-way Catalyst [5]

- A: Reduction Catalyst
- B: Oxidation Catalyst
- C: Honeycomb Structure

One of the drawbacks of the dual catalysts systems is that the NOx reduction catalyst produces significant amounts of ammonia (NH_3), which is then oxidized in the oxidation catalyst, forming NOx again. To combat this problem a great deal of research has been conducted on the washcoat materials and it has been found that through the use of platinum/rhodium as the catalyst materials, the ammonia production can be minimized. Further development revealed the potential for these platinum/rhodium catalysts to control CO, UHC, and NOx, negating the need for a second oxidation catalyst. The drawback is the need for very precisely controlled stoichiometric combustion. The perturbation in the air/fuel ratio for these systems is typically +/- 0.25. For most applications this required the use of an electronic fuel injection system with lambda loop feedback, greatly adding to the cost of the engine [1]. Figure 3 shows the relationship between conversion efficiency and equivalence ratio for the three types of catalysts and highlights the equivalence ratio at which each should be used.

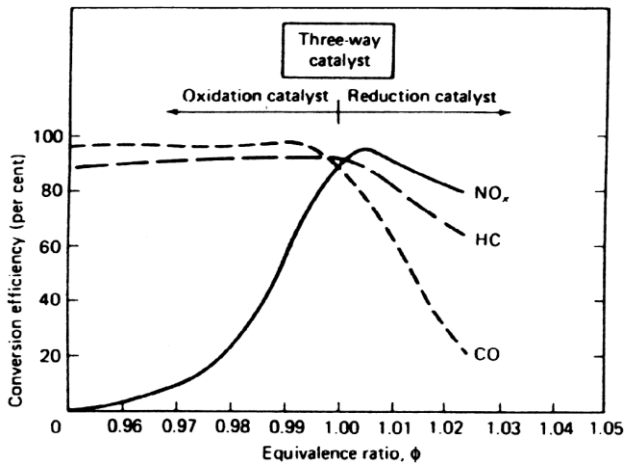


Figure 3: Conversion efficiencies of catalyst systems. [1]

CATALYST DURABILITY

Durability is a major concern in the design and construction of catalysts. The change in a catalyst over time is known as catalyst aging. As a catalyst ages, there are three distinct effects on its performance. First of all the light-off temperature rises, secondly the conversion efficiency falls, and third the catalyst's response to different components in the exhaust changes [1].

The mechanisms that cause these effects are catalyst poisoning, failure of the substrate, and sintering. Catalyst poisoning is the de-activation of the catalytic material through deposits from leaded fuel, sulphur, and lubricant additives such as phosphorus. This is of particular interest for two-cycle applications because they incorporate a waste oil system that allows some lubricant to pass into the combustion chamber with the fresh air charge. This combined with the fact that many two-cycle lubricants contain high amounts of phosphorus can lead to rapid poisoning of the catalyst. This problem is not easily addressed in the design of the catalyst but can be remedied by ensuring that the lubricant used has as low of phosphorus content as possible. Another mechanism through which aging occurs is failure of the substrate itself. The substrate is the ceramic or metal material that forms the bulk of the converter. This material can be sensitive to thermal shocks and must be designed accordingly for the application. The most destructive thermal shocks for the substrate typically come from misfiring. The final mechanism for catalyst aging is sintering, or the process by which the catalytic material agglomerates and its effective area is reduced. This process occurs when the catalyst is subjected to high temperatures for long periods of time [1].

CATALYST LIGHT-OFF

Catalyst light-off time is defined as the time it takes for 50% of the specified gasses to be converted. The main factor affecting catalyst light-off is the placement of the catalyst in respect to the manifold. The closer the catalyst is placed to the manifold the faster the light-off time [2]. Catalyst light-off is a very important factor in catalyst design due to the high levels of emissions released during the cold start period.

For the CSC project emissions are only tested after the engine and catalyst have reached operating temperature, therefore catalyst light-off time is not important and the design must only ensure that the catalyst will light-off at normal engine operating temperatures. It should be noted that catalyst efficiencies typically increase with catalyst temperature so the thermal properties of the catalyst should not be neglected entirely.

CATALYST SHAPE

The shape of the catalyst is of extra importance in two-stroke applications. Two-stroke cycle engines rely on highly tuned exhaust systems to maximize their specific output. The addition of a catalyst to the exhaust system adds backpressure, which in turn has a detrimental effect on the ability of the exhaust system to be properly tuned. In a non-DI two-stroke cycle engine this process can also greatly affect emissions because the pressure waves in the exhaust are timed to help hold the fresh fuel charge in the combustion chamber until the exhaust port is covered. For DI two-strokes the effect on the emissions is not as high because the fuel is not injected until after the exhaust port is closed. It does however limit the scavenging efficiency, resulting in a diluted fresh air charge and lower specific power. One benefit is that this natural EGR decreases flame temperature and thus lowers NO_x emissions.

To minimize backpressure, Auth [2], found research indicating that increased frontal area decreases the pressure drop across the converter and increasing the length of the converter increases the pressure drop. The trade-off is that the converter length is directly proportional to the conversion efficiency, the longer the converter, the greater the efficiency.

In addition to shape, the design of the catalyst substrate is also an important factor in the backpressure created by the catalyst. The two main types of substrates are honeycomb substrates and ceramic bead substrates. The honeycomb substrate is the most widely used in the automotive industry today and is considered superior to the ceramic bead substrate in all aspects. Figure 4 shows a cutaway of an automotive honeycomb substrate.



Figure 4: Honeycomb Substrate [5]

In order to minimize the backpressure created by the catalyst the cell density of the substrate should be made as small as possible. This effectively increases the size of the passages through the catalyst and therefore provides less flow restriction. The tradeoff is that the decreased cell density provides less surface area, decreasing the conversion efficiency of the catalyst. Therefore, a careful balance must be maintained between backpressure and conversion efficiency.

CONCLUSION

Given the slightly rich operating conditions and emission characteristics of the University of Idaho's CSC entry, several conclusions can be drawn on catalyst selection. Even though the primary emission species of concern are UHC and CO, NO_x is still a factor and all three can be reduced through the use of a three-way catalyst. Given the advanced platinum/rhodium three-way catalysts that are currently available, the tradeoff between NO_x reduction and UHC and CO oxidation is negligible. This three-way catalyst does require an advanced engine management system, but this is already planned for the CSC entry to control the complex

direct injection system. Also, the effects of the NO_x reduction capabilities of the catalyst will be maximized because of the slightly rich combustion condition. The catalyst composition does not need to be exotic due to how closely the emissions of the GDI match those of a typical automotive 4-stroke cycle engine. The most advanced automotive catalysts will work equally as well on the GDI engine. In order to minimize the pressure drop across the converter, the frontal area of the converter should be made as large as possible while minimizing the length of the converter. The length of the converter and cell density must be balanced to ensure high enough conversion efficiency but not introduce excessive amounts of backpressure. The combination of these catalyst characteristics will provide a viable catalyst design that will ensure the University of Idaho CSC Team's success at the 2003 competition.

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