

Design and Implementation of a D-EGR® Mixer for Improved Dilution and Reformate Distribution

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ABSTRACT

The Dedicated EGR (D-EGR®) engine has shown improved efficiency and emissions while minimizing the challenges of traditional cooled EGR. The concept combines the benefits of cooled EGR with additional improvements resulting from in-cylinder fuel reformation. The fuel reformation takes place in the dedicated cylinder, which is also responsible for producing the diluents for the engine (EGR). The D-EGR system does present its own set of challenges. Because only one out of four cylinders is providing all of the dilution and reformate for the engine, there are three “missing” EGR pulses and problems with EGR distribution to all 4 cylinders exist. In testing, distribution problems were realized which led to poor engine operation. To address these spatial and temporal mixing challenges, a distribution mixer was developed and tested which improved cylinder-to-cylinder and cycle-to-cycle variation of EGR rate through improved EGR distribution. This paper will discuss the process by which the mixer was designed and compare alternative solutions to the final mixer design. Engine data with and without the mixer in place will be shown to demonstrate the level of EGR distribution improvement.

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INTRODUCTION

As concerns over climate change and fuel prices escalate, increased regulations have been put in place to reduce emissions and provide energy security. The automotive industry is faced with the challenge of reducing CO₂ emissions by at least 30% and tailpipe emissions by a factor of 3 by 2025 [2]. With increasing regulations, manufacturers and researchers are being forced to develop new engine concepts and combustion strategies. One of the routes to higher efficiency, low emission engines is through the use of cooled exhaust gas recirculation (EGR). Improvements from EGR can be realized by increasing the indicated cycle efficiency and reducing in-cylinder heat transfer and throttling losses. Cooled EGR also reduces the knocking tendencies of the engine, thereby enabling a higher compression ratio or extending the operating range where optimal combustion phasing can be achieved. In addition to the cycle efficiency and knocking improvements, EGR can reduce NO_x, CO, PM, and PN emissions [5,6]. EGR can be utilized on an engine with relatively minor modifications and real world fuel consumption improvements of >5% can be realized.

However, the addition of cooled EGR does not come without certain challenges. Some of the challenges are misfire, combustion stability and EGR metering [2]. The addition of EGR decreases burn velocities which can lead to unstable combustion. The addition of dilution also increases the need for a high energy ignition such as a multi strike or continuous discharge system, to properly ignite the dilute mixture. In a naturally aspirated (NA) engine or with a factory boosting system, EGR can reduce the volumetric efficiency of the

engine. Because the pumping reduction comes from the decrease in volumetric efficiency; the specific output of the engine is reduced when compared to a non-dilute engine. D-EGR was invented to address the shortcomings of cooled-EGR while maintaining or exceeding the efficiency benefits.

DEDICATED EGR CONCEPT

The D-EGR concept involves the use of one of more cylinders to generate the EGR used by the engine. This EGR is produced solely by those cylinder(s) and routed back into the engine's intake. Additionally, the dedicated cylinder(s) can be operated rich of stoichiometric to produce CO and H₂. A schematic of the concept is shown in [Figure 1](#).

The presence of H₂ results in significantly faster flame propagation rates and improves combustion stability at higher dilution rates [7,8]. Additionally, the higher octane ratings of the CO (RON 106) and H₂ (RON 130) play a role in improving the knock tolerance of the engine.

However, because of the pulsed nature of EGR flow in a D-EGR engine, significant challenges are posed in regards to EGR distribution [9]. As the whole engine is reliant on not only the dilution, but the CO and H₂ as well, ensuring that each cylinder receives similar dilution is of high importance.

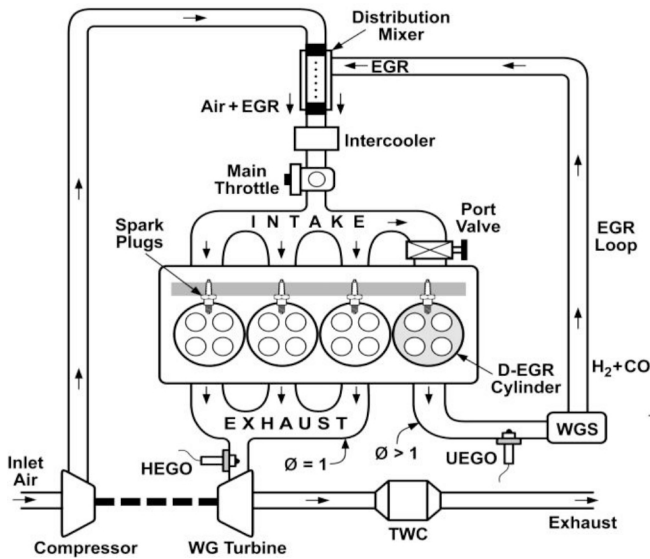


Figure 1. D-EGR Engine Schematic

The primary objective of this study is to investigate the importance of a D-EGR distribution mixer and how it affects engine operation over a variety of speed and load conditions.

EXPERIMENTAL SETUP

The engine used in this study was a 2.0 L MPI inline 4-cylinder engine. The engine was instrumented with typical laboratory instrumentation including engine speed, torque and fuel flow, as well as various pressure and temperature measurements. Additionally, the engine was equipped with in-cylinder indication via pressure transducers manufactured by Kistler and a high speed data acquisition system developed by SwRI. In its baseline configuration, the engine was rated at a peak torque of 300 N·m at 2,250 rpm and a maximum power of 180 hp was achieved at 5,500 rpm. Upon the conversion to D-EGR, the turbocharger was replaced with a twin scroll unit from a 1.6L engine. Engine control was performed through a custom SwRI developed prototyping ECU based on National Instruments cRIO hardware. To assist with igniting the dilute mixture, a Dual Coil Offset (DCO[®]) high energy ignition system was installed. The DCO system allowed for a continuous spark to be supplied to the prepared mixture. The main coil was dwelled with the second coil being charged a few hundred microseconds later. Once the main coil was discharged, the second coil was continuing to charge. The two coils were then alternated between charging and discharging to allow for one continuous discharge of spark energy. The overall energy supplied was controlled by increasing the number of discharges, or restrikes, shown in Figure 2.

This system could be operated in single strike, multi strike or DCO mode [1, 2]. For all of the testing, the ignition was operated in DCO mode and the ignition energy was controlled to ~400 mJ. As cooled EGR and reformat both reduce knock, the compression ratio of the engine was increased from 9.1:1 to 12.5:1. The base engine specifications are shown in Table 1.

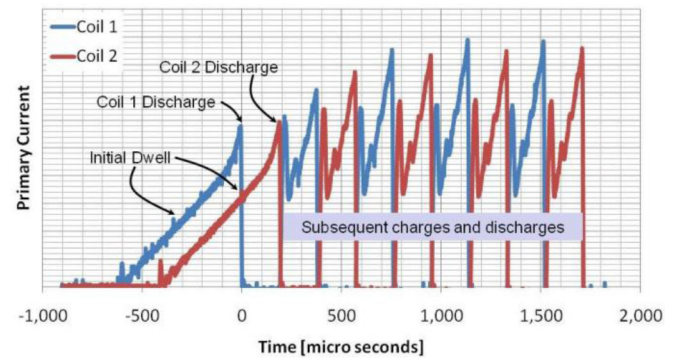


Figure 2. Dual Coil Offset (DCO) primary current waveform

Table 1. Base Engine Specifications

Displaced volume	1998 cc
Stroke	82.7 mm
Bore	93.0 mm
Compression ratio	9.1:1
Number of Valves / cylinders	16 / inline 4
Maximum Power	180 hp at 5,500 rpm
Maximum Torque	300 Nm at 2,250 rpm
Injection	Multiport Sequential
EGR Type	Dedicated EGR

RESULTS AND DISCUSSION

Initial testing of the D-EGR system utilized a simple pipe “T-insertion” to establish a baseline and evaluate the impact of introducing non-temporally or spatially mixed EGR into the intake stream. The pulsed nature of the EGR flow combined with pulses of the intake at 4x the EGR pulse-frequency led to high levels of instability during operation. Depending on operating conditions, some cylinders would misfire from excessive dilution, while others would exhibit excessive knocking, indicative of too little dilution. This was caused by slug flow of EGR in the intake stream resulting in some cylinders receiving too much dilution and others too little. Previous testing of a D-EGR engine showed the impact of maldistribution on the engine. Representative combustion parameters from this testing are shown in Figure 3. At the engine condition shown, the IMEP of the engine showed a high variation between cylinders. Because some cylinders received more fresh air than others, a difference in peak cylinder pressures can be seen. Additionally, burn rates in the high-EGR cylinders would be longer. Finally, the maldistribution effects stability. Due to the lack of EGR in some cylinders, knock was encountered which required spark retard to suppress. However, other cylinders suffered from excess EGR which prevented any additional spark retard as this would have made the engine unstable. The combination of certain cylinders knocking and others misfiring simultaneously, lead to high variation in the location of peak pressure and much higher standard deviation than the conventional EGR engine.