

Condensing LPL EGR Mixer with Mid-Pressure Loop

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ABSTRACT

Cooled LPL EGR is a proven means of improving the efficiency of a Gasoline Turbocharged Direct-Injection engine. One of the most significant hurdles to overcome in implementing a LPL EGR system is dealing with condensation of water near the entrance of the turbocharger's compressor wheel. A gasoline engine, and to a greater extent a spark ignition engine running on Natural Gas, will encounter enough water condensation at some steady-state conditions to damage the compressor wheel due to the high-speed collision between the compressor blades and the water droplets. As an alternative to not utilizing beneficial EGR at the condensing conditions, the team at BorgWarner have developed a LPL EGR mixer that is effective at condensing and collecting the water droplets and routing the water around the compressor wheel.

The new Condensing EGR mixer was developed from the known concept of utilizing a mild venturi section to enhance EGR delivery and mixing. The developed system was designed to both maximize condensation and separation of liquid water from the EGR stream, as well as manage its disposal through the engine in a manner that both avoids damage to the compressor and minimizes liquid freezing potential in very low ambient conditions. The system architecture includes a Mid-Pressure path that is utilized to both purge the system of liquid water as, well as provide engine efficiency improvements at moderate load operation points compared to utilizing pure LPL EGR.

In this paper we present the system design concept and engine test results of the prototype mixer.

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INTRODUCTION

In an engine equipped with a Low Pressure Loop (LPL) EGR system, the junction upstream of the compressor wheel where the fresh air and exhaust gas mix is the most favorable point in the system for condensation. A gasoline engine, and to a greater extent a spark ignition engine running on Natural Gas, will encounter enough water condensation at some steady-state conditions to quickly damage the compressor wheel due to the high-speed collision between the compressor blades and the water droplets [1]. These conditions are a function of ambient temperature and humidity as well as the engine speed and load, engine temperature, and EGR rate. In addition, vehicle under-hood airflow and thermal management will significantly affect the surface temperatures along the entire EGR and airflow paths. Due to the large number of variables that can effect condensation, a robust means of managing LPL condensate is needed.

The new Condensing EGR Mixer has been developed as a compact module that mounts to, or can be incorporated into the turbocharger compressor housing and includes an integrated EGR valve. The mixer was developed from the known concept of utilizing a mild venturi section to enhance EGR delivery and mixing. This is the favored method of delivering LPL EGR in the Southwest Research Institute's HEDGE-2 Consortium engine testing. The developed

system was designed to both maximize condensation and separation of liquid water from the EGR stream, as well as manage its disposal through the engine in a manner that both avoids damage to the compressor and minimizes liquid freezing potential in very low ambient conditions. To manage the collected condensate we have devised and tested an EGR/condensate "Mid-Pressure" path that is utilized to both purge the system of liquid water as, well as provide for an additional EGR route.

EGR SYSTEM ARCHITECTURE

As discussed in previous publications [2,3,4], internal and external EGR can provide significant fuel efficiency and emissions benefits to gasoline spark-ignition engines throughout their operating range. The entire speed and load range of the engine can be effectively covered by combining internal EGR via camphasers at low engine speed and load, with LPL covering the rest of the engine operating range. An additional case can be made for adding an uncooled EGR High Pressure Loop (HPL) at moderate to high engine speeds and loads to further optimize Brake Specific Fuel Consumption (BSFC), as shown in this graph (Figure 1) from [3]:

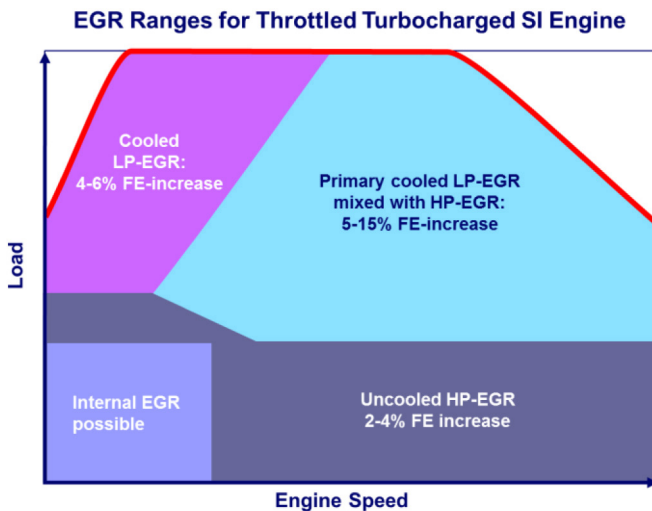


Figure 1. EGR System Coverage of Engine Map (from[3])

Since most current turbocharged engines have dual camphasers, which provide nearly ideal mounts of internal EGR at light load and low engine speed, the first production gasoline turbocharged engines with cooled external EGR will utilize the LPL architecture to fill-out the rest of the engine operation map with amounts of EGR necessary to improve moderate to high load BSFC.[5] A typical LPL EGR arrangement is shown in Figure 2.

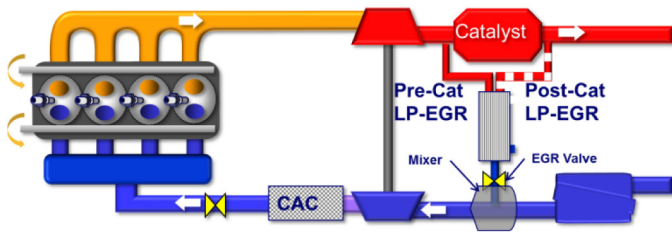


Figure 2. LPL System Architecture

The LPL EGR may be sourced from either before or after the catalytic converter, but the currently favored strategy is post-catalyst EGR since it is expected to yield significantly lower rates of fouling and corrosion on the components in the air path. Of particular concern are the surfaces of the compressor, Charge Air cooler (CAC), and engine throttle. The authors note that at this time there is little published about these effects for gasoline engines.

CONDENSATION MANAGEMENT

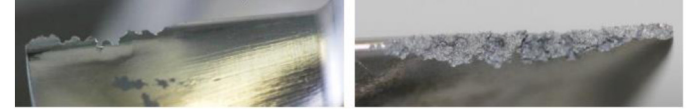
The junction of EGR and the fresh-air paths upstream of the entrance to the turbocharger compressor is the most-likely location for formation of condensed water droplets because the exhaust gas in the EGR path is cooled as it travels through the EGR cooler and associated piping. Depending on conditions, droplets may form anywhere in this path and most-likely in the mixing junction; even if this is a simple “T” shaped junction, since the junction is cooled by the near-ambient temperature airflow coming from the aircleaner assembly. Compressor wheel damage from condensed droplets has

been observed in the field in production Diesel engines and studied on a test bench [1]. Damage is a function of droplet size, quantity, location and turbocharger speed and can be catastrophic as seen in results from [1] shown in Figure 3.

#1) Orifice 500 $\mu\text{m} \pm 1120 \mu\text{m } d_{p, \text{top}}$; Frequency 9 kHz



#2) Orifice 250 $\mu\text{m} \pm 470 \mu\text{m } d_{p, \text{top}}$; Frequency 18 kHz



#3) Orifice 150 $\mu\text{m} \pm 340 \mu\text{m } d_{p, \text{top}}$; Frequency 20 kHz



#4) Orifice 100 $\mu\text{m} \pm 153 \mu\text{m } d_{p, \text{top}}$; Frequency 45 kHz

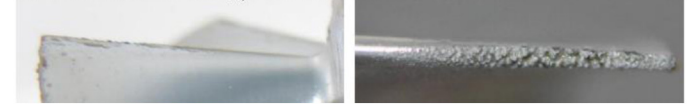


Figure 3. Compressor Blade Damage For Different Water Injection Parameters (from [1])

Prediction of condensation by calculation is greatly complicated by the fact that the heat transfer in the EGR path is not just a function of the characteristics of the EGR cooler and the EGR source temperature but also significantly affected by heat transfer from the EGR piping and even the EGR valve itself, and this heat transfer is dependent on the underhood air temperatures and velocities which in-turn are functions of:

- Ambient air temperature
- Vehicle speed
- Ambient wind velocity and direction
- Vehicle-to-vehicle variations in underhood airflow

Therefore, any calibration strategy of avoiding the possibility of compressor damage from condensed water droplets by shutting off LPL EGR delivery, will require a significant safety factor beyond what might be determined based on steady-state and transient measurements on an engine dynamometer.

Estimation of LPL EGR Condensation Range

To prepare for an evaluation of the new EGR mixer we undertook a series of tests to determine the approximate ranges for steady-state conditions of condensation on turbocharged GDI engine installed on an engine dynamometer at near-standard conditions of ambient temperature and humidity. We utilized a production engine with the specifications shown in Table 1:

Table 1. Test Engine Specifications

Engine Type	GDI Turbo
Displacement	1998 cm ³
Valvetrain Type	DOHC w/ roller finger follower, Dual Cam-Phasers
Compression Ratio	9.2:1
Max. Torque @ engine speed	350 Nm 2000 rpm
Max. Power @ engine speed	194 kW / 260 HP 5300 rpm

For this series of tests, the engine was equipped with a LPL EGR system comprised of 20mm inside diameter stainless-steel tubing, a BorgWarner EGR valve and EGR cooler. The EGR path was, at approximately 1.5 meters total length, approximately twice the likely achievable length in a production under-hood application. The cooler had dimensions of 60mm × 60mm section by 220mm length and was supplied by engine coolant in the heater core coolant loop. The EGR mixer was a Stainless-steel fabricated “T” mixer. The test cell temperature was maintained at 21°C, the engine coolant at 86°C, and the combustion air was supplied to the engine at controlled temperature and humidity. Condensation was judged by observing a sight-glass installed at the entrance of the compressor (Figure 4) during a 10-minute steady-state run at the conditions shown in Table 2.

Table 2. Steady-State Observation of Pre-Compressor Condensation with LPL EGR

Speed	Load	EGR %	RH%	Air Temp	Condensation
2000	6bar	8	50	25°C	Yes
2000	8bar	8	50	25°C	Minimal
2000	10bar	8	50	25°C	No
2000	6bar	8	38	25°C	Minimal
2000	8bar	8	38	25°C	No
1500	4bar	5	38	25°C	No
1500	4bar	8	38	25°C	No
1500	4bar	5	50	25°C	Yes
1500	4bar	8	50	25°C	No
2500	6bar	8	50	25°C	Yes
2500	8bar	8	50	25°C	No
2500	6bar	8	40	25°C	No

Some observations about steady-state condensation limits are:

- As engine load rises, the likelihood of condensation reduces due to the increase of EGR source temperature and reduced temperature reduction through the EGR cooler and pipes
- As EGR rate rises, the condensation likelihood reduces due to the reduced temperature drop through the EGR cooler and pipes

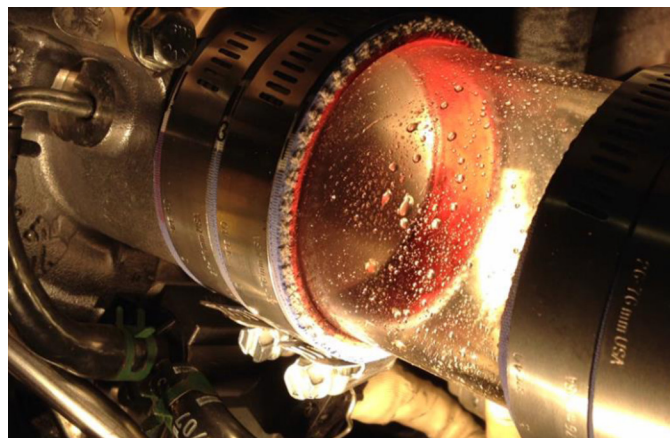


Figure 4. Observation of Steady-State Condensation on Engine Test Bench

Based on these results, for which the ambient conditions are clearly within the bounds of normal operation of a passenger vehicle operating on standard regulated test cycles, steady-state condensation can occur at engine loads up to 6 Bar BMEP and ambient conditions up to 77°C at 50% relative humidity. Of course typical “winter” conditions will increase the range of steady-state condensation.

CONDENSING MIXER WITH MID-PRESSURE LOOP

In our early EGR tests we modified a natural-gas carburetor for use as an EGR-mixer and observed that the thin-wall aluminum venturi section provided an enhanced surface for condensation of water from the incoming EGR stream due to the large surface area on the outside of the venturi section, combined with the natural cooling of that surface by the incoming fresh air stream. The basic principle is shown below in Figure 5.

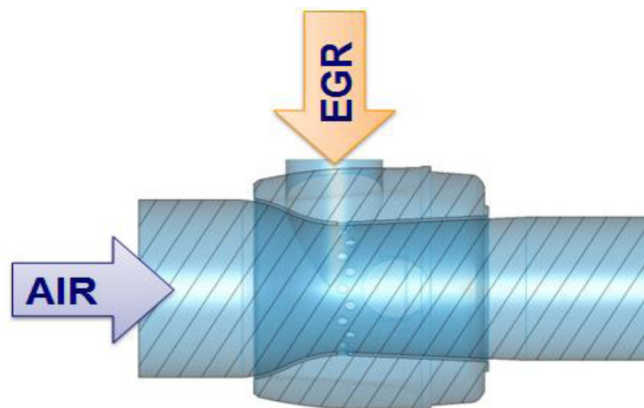


Figure 5. Principle of Venturi Section as EGR Mixer

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