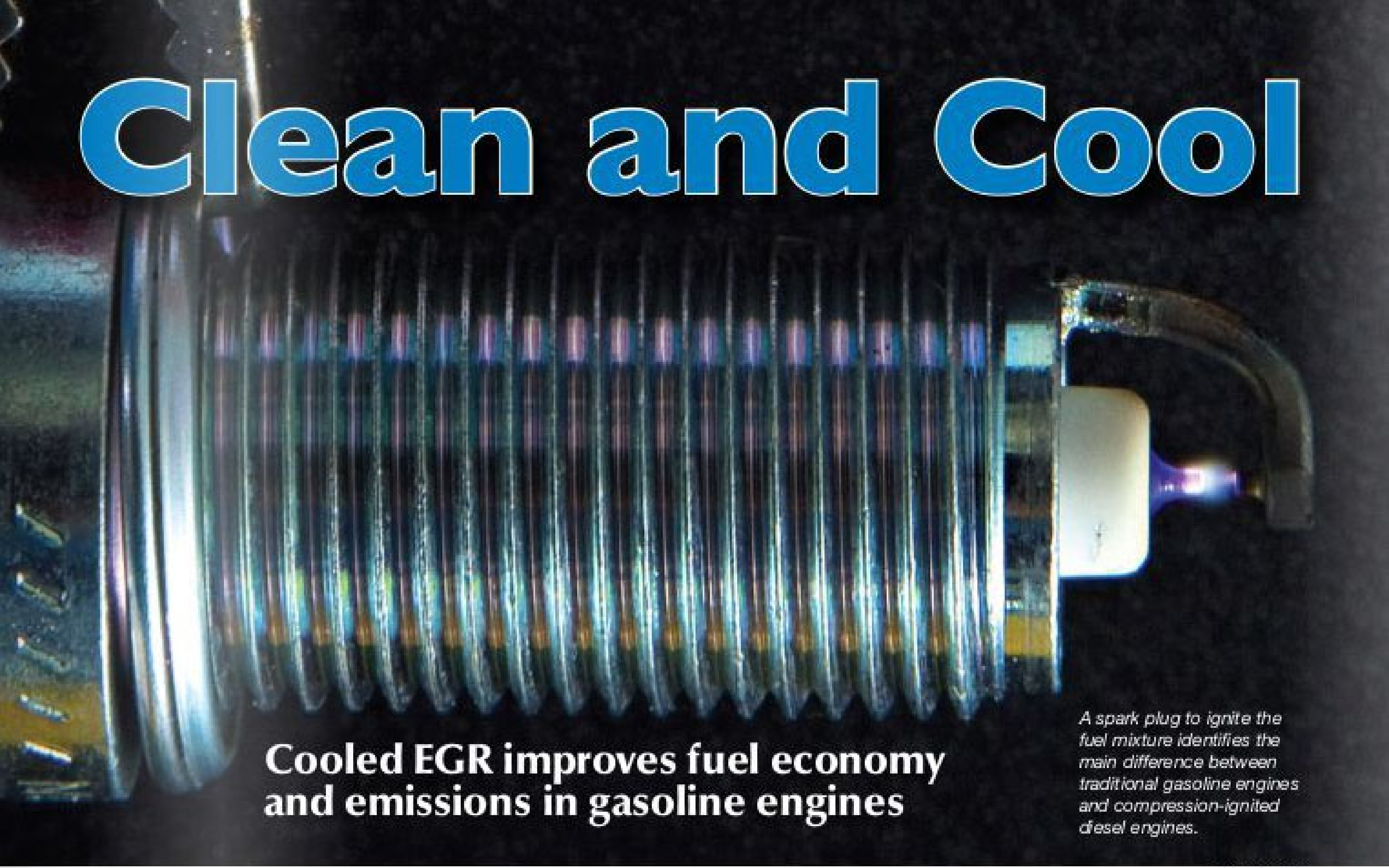
Clean and Cool



Cooled EGR improves fuel economy and emissions in gasoline engines

A spark plug to ignite the fuel mixture identifies the main difference between traditional gasoline engines and compression-ignited diesel engines.

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By Terry Alger, Ph.D.

Modern gasoline engines face fuel efficiency challenges due to a number of limitations that are inherent to the Otto cycle that defines the spark-ignited engine. With many governments beginning to regulate CO_2 emissions, the spark-ignited engine must continue to improve its efficiency to remain the powertrain of choice for light-duty (automotive) applications while continuing to produce ultra-low emissions.

For alternative applications that would typically require a diesel engine, the ultra-low emissions capability of the spark-ignited engine is an attractive benefit, given the increased cost and effort required for the traditional diesel engine to meet modern emissions standards. However, to be a realistic competitor to a diesel engine, spark-ignited engines must improve their fuel efficiency.

Unfortunately, addressing one aspect of inefficiency frequently means making a trade-off with separate inefficiencies elsewhere in the combustion or exhaust cycle. For example, strict emissions regulations require that most typical gasoline engines maintain a fixed, stoichiometric air-fuel ratio to ensure proper functioning of the three-way catalyst that removes pollutants from the exhaust. However, to achieve this ratio in low-load conditions requires throttling, or restricting air flow, which leads to efficiency losses called pumping losses. A commonly proposed method to reduce pumping losses is to decrease engine displacement and use a turbocharger to increase the power output. Since the vehicle power requirements will not change, the reduced-displacement engine must operate at higher levels of specific power output, greatly reducing the need to operate the engine at the lowest loads. However, there is a catch.

At high loads, knock is a more significant source of efficiency losses than pumping work. Knock is the spontaneous ignition of part of the charge. This can lead to excessively high cylinder temperatures and pressures as well as objectionable noise. If allowed to occur continually, knock can also cause significant engine damage. Knock is addressed in a number of different ways in engines, including reducing the compression ratio and retarding spark timing. While it is possible to achieve good fuel consumption results at high power levels and reduced compression ratios, the fuel consumption at low to partial loads is often compromised. Using spark-retard to combat knock leads to reduced efficiency and excessive exhaust temperatures at high loads.

Typically, the solution to the exhaust temperature problem has been to enrich the fuel-air mixture to reduce combustion temperatures. This not only wastes fuel, but it also makes it difficult to meet carbon monoxide (CO) and hydrocarbon (HC) emissions standards at high loads and, although they are not currently regulated, also leads to very high levels of particulate emissions (PM).

Recent studies performed by engineers at Southwest Research Institute (SwRI) have examined the role that exhaust gas recirculation (EGR) can play in reducing, or even eliminating, these sources of inefficiency in gasoline engines. In internally funded research, they determined that EGR can improve the fuel consumption of both direct-injected and port-injected gasoline engines by reducing pumping losses, mitigating knock, cooling the exhaust and eliminating the need for fuel enrichment.

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At low loads, the use of either internally recirculated exhaust gas, commonly referred to as burned residual, or externally recirculated exhaust gas (EGR) has been shown to reduce pumping losses through the combined effects of displacing intake air and decreasing the charge density through heating. Meanwhile, at high loads the addition of cooled EGR substantially reduces the knock tendency of the engine, resulting in an opportunity to advance combustion phasing and improve the combustion cycle efficiency.

In addition, combining advanced combustion phasing with increased heat capacity of the fuel-air mix results in a substantial decrease in exhaust temperatures. This eliminates the need for a rich mixture at even the highest power levels. Finally, EGR has been shown to reduce emissions of carbon monoxide (CO) and particulate matter (PM) as well as oxides of nitrogen (NOx).

Engine study

The SwRI team selected a 2.4L port-injected engine and 1.6L direct-injected engine for the study. Each was run with high levels of both cooled and uncooled EGR. Both engines were turbocharged. The purpose of selecting two types of fuel injection systems was to determine whether the benefits of EGR can be realized across engine platforms.

A prototype EGR system was installed on each engine, consisting of an EGR cooler and valve installed in such a manner as to route exhaust gas from the turbine outlet to the compressor inlet. SwRI engineers designed the system to limit back pressure on the engine and reduce hot internal residual and knocking at low speeds and high loads.

The ideal efficiency of an Otto-cycle engine is a function of compression ratio (r_c) and the ratio of specific heats of the working fluid (γ), expressed thus: $\eta_{ti} = 1 - 1/r_c^{\gamma-1}$

For a given engine, the compression ratio (r_c) is fixed; therefore, the primary way to affect the fundamental efficiency is to increase the ratio of specific heats of the working fluid. For a typical pre-mixed gasoline engine at wide-open throttle, the working fluid consists of approximately 8 percent burned residual, 86 percent air and 6 percent gasoline. At room temperature, the γ of burned gases is about 1.3; air has a γ of 1.4 and gasoline has a γ of approximately 1. When the EGR level of the engine is increased, the mass fraction of the gasoline is reduced; therefore, despite the lower value of γ for burned gases compared to air, the overall ratio of specific heats for the mixture increases. When EGR was added, although the difference in specific heat ratio appeared small it was enough to result in more than a 1 percentage point increase in thermal efficiency with 20 percent additional EGR.

In addition, adding EGR increased the specific heat capacity and thermal mass of the fuel-air mix, resulting in lower peak temperatures during combustion. Lower combustion temperatures result in a reduction of heat transfer losses, as the majority of the heat transfer losses occur during and after the combustion event, when the surface area to volume ratio of the engine was maximized.

Another significant source of losses in an internal combustion engine is heat transfer to the engine coolant. By reducing the peak temperatures, the use of high levels of EGR reduced the amount of heat transfer to the engine coolant, improving efficiency. For example, at the 1500 rpm / 191 N-m brake torque (30 kW brake power) condition, the addition of EGR reduced the engine's heat transfer to the coolant by approximately 6 kW, or 20 percent of the total engine power output.

Given the industry trend of downsizing and boosting, which leads to operation at high specific power levels, the most significant effect of EGR addition is on combustion phasing. Adding EGR slowed reaction rates, leading to longer burn rates and the suppression of knock, yielding more advanced spark timing and allowing more optimized combustion phasing. In addition, the improvement in combustion phasing with EGR was not limited to port-injection engines. Despite the recognized improvement in the knock limit from direct-injection engines, EGR can also have a considerable impact on combustion phasing in that engine. The improvement in combustion phasing can result in as much as a 10-15 percent improvement in fuel consumption at a given engine speed and torque and, for future engines, enables the use of higher compression ratios at elevated torque levels.

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SwRI's proprietary Dual Coil Offset (DCO) ignition system significantly extends the EGR tolerance of gasoline engines, enabling higher efficiency operation.

Fuel efficiency

Another significant source of fuel consumption improvement at high load was the elimination of the enrichment region. The primary reason for the presence of the enrichment region is to keep exhaust manifold temperatures below the supplier's prescribed limit of 900 degrees C, with excess fuel being the primary source of cooling. The result of the enrichment requirement is an increase in the relative fuel-air ratio along the wide-open throttle curve. Depending on the specific power level and the engine design, the engine could run as much as 50 percent excess fuel or more to keep the temperature below the limit. This, in turn, leads to fuel consumption values in excess of 300 g/kWh.

Adding EGR can reduce the enrichment requirement through two mechanisms. The first is through increasing the specific heat and thermal mass of the mixture, which results in lower peak combustion temperatures and a general decrease in cycle temperatures. The second is through allowing more spark advance and moving the location of peak temperature earlier in the cycle. This increases the expansion ratio of the gas and results in lower temperatures at blowdown and during the exhaust event.

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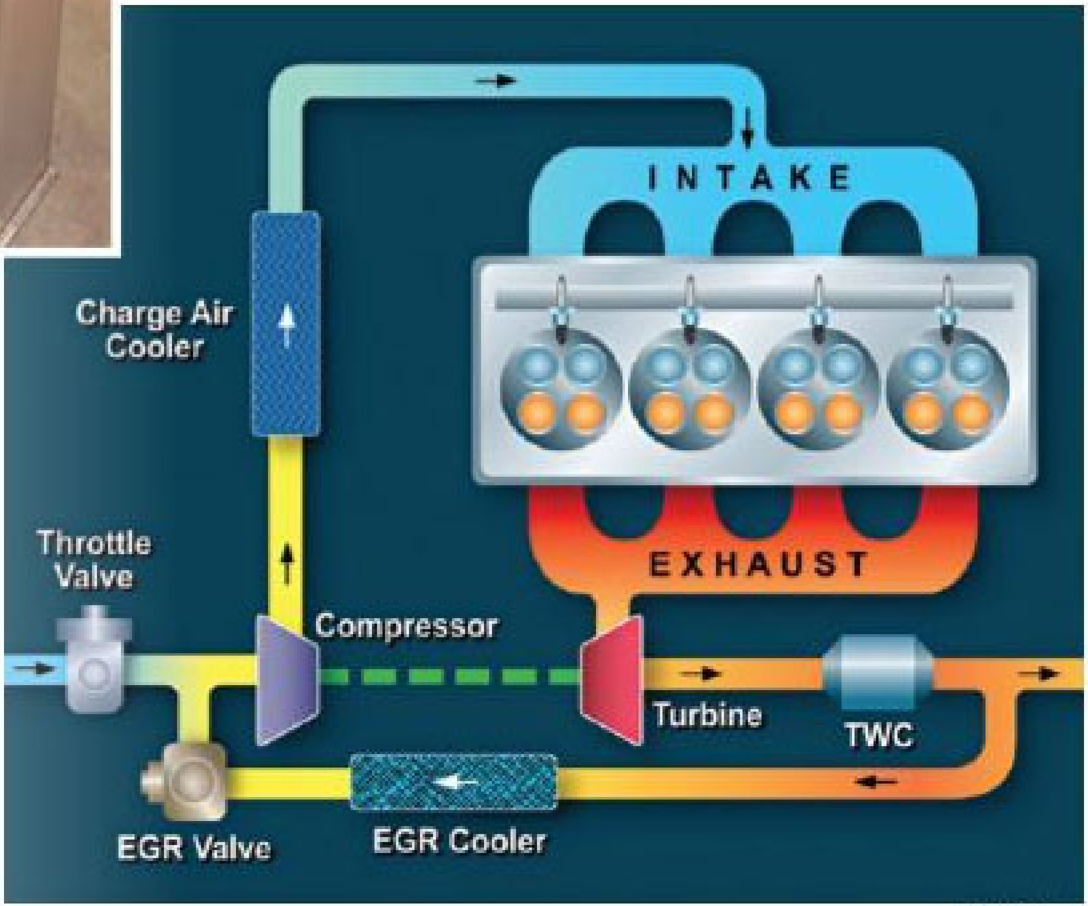
EGR coolers are a key component to enabling high efficiency. Exhaust gases flow through the cooler, which is bathed in engine coolant.

The end result of this mechanism was a reduction in exhaust gas temperature of about 5 degrees C per 1 percent of EGR on average. In general, at least 10 percent of EGR was required to eliminate the enrichment requirement altogether and still maintain the exhaust temperature below the 900-degree limit.

Pumping loss reduction

The addition of EGR also served to reduce pumping losses in the engine. At part load conditions, when the engine intake manifold pressure was less than the atmospheric pressure, adding EGR (either internal or external) resulted in a small reduction of pumping losses, with a corresponding slight improvement of fuel consumption. However, the point of lowest pumping loss is not the point of least fuel consumption. This is because the fuel burn rate and engine stability both degrade with the addition of diluent. At high loads, the reduction in the burn rate was desirable, because the same mechanism reduces the likelihood of knock, but at low loads the engine rapidly became unstable. At very low loads, those losses can be up to 30 percent of the engine's brake power. A main accomplishment of SwRI's HEDGE I consortium was developing an ignition system that allows the engine to run at high diluent levels and still remain stable. SwRI's DCO™ system has shown the ability to improve EGR tolerance in a gasoline engine by a factor of 4 at low load conditions. However, it appears as if the pumping loss reduction is the least significant benefit from EGR at higher loads.

The results presented above for efficiency illustrate the potential benefits of using a high EGR scheme to improve fuel consumption. However, they do not take into account improvements that are allowed to the engine hardware, primarily through the reduction of knock. In the optimal situation, knock reduction due to EGR can allow engine designers to either increase the level of downsizing



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This schematic of an engine fitted with cooled exhaust gas recirculation (EGR) illustrates how the hottest exhaust gases, shown in red and orange, are cooled (yellow) before being recirculated amid the cooler (blue) ambient air in the intake.

or down-speeding, or increase the compression ratio. This opportunity, if properly taken advantage of, can lead to even larger improvements in vehicle fuel efficiency.

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Members of the HEDGE consortium research team within SwRI's Engine, Emissions and Vehicle Research Division, left to right: Dr. Charles E. Roberts Jr., Institute engineer; Dr. Terry Alger, manager; Patricia Gamboa, administrative assistant; Dr. Michael Joo, senior research engineer; Jess Gingrich, senior research engineer; Dr. Zainal Abidin, research engineer; Barrett Mangold, research technologist; Rafael Gukelberger, intern; Steven Almaraz, research assistant; and Craig Gibson, principal technician.

Emissions reductions

At high levels of EGR, the reduction in peak combustion temperatures resulted in a significant reduction in two of the three primary pollutants. Since the 1970s, EGR has been used to reduce NOx. In fact, NOx can be reduced by up to 80 percent with the addition of more than 20 percent EGR.

While the level of NOx reduction was high, it was an expected result of adding EGR. What is more interesting is the level of reduction in CO that occurred as well. When the engine is stable, CO emissions are primarily influenced by combustion temperatures and pressures, as the dissociation of CO_2 into CO and O_2 is highly temperature- and pressure-dependent (similar to the NOx reactions). The addition of EGR, and the corresponding reduction in combustion temperatures and increase in pressure, can suppress this dissociation reaction. The SwRI team achieved a 50 percent reduction in CO emissions from the engines involved in its EGR research. The only pollutant that appeared to be adversely affected by EGR addition was unburned hydrocarbons (HC), whose emissions increased slightly with the addition of cooled EGR. The primary mechanisms for the increase were increased quench distances and partial combustion, as well as cooled post-flame temperatures. The combination of reduced combustion temperatures and engine instability as the EGR limit was approached led to the increase in HC emissions in the port-injected engine near 30 percent EGR. However, it should be noted that the overall level of HC emissions was still within the range controllable by a three-way catalyst.

Overall, the results showed that engine-out NOx was approximately four times lower than a typical engine and CO emissions were cut in half. HC emissions increased slightly, but still within reason for an oxidation catalyst or three-way catalyst.

In addition to reducing two of the three primary pollutants from gasoline engines regulated by the EPA, the addition of EGR also has been shown to reduce the emission of particulates (PM). The reduction in PM emissions has been attributed to reduced combustion temperature suppressing the PM formation rate. In addition, at high loads, the reduction in enrichment leads to a significant reduction in PM emissions as the presence of a rich mixture (excess fuel) leads to very high PM emissions, even in pre-mixed gasoline engines. SwRI has initiated an internally funded project to investigate the effect of our cooled EGR technology on the PM emissions from a direct-injection engine, where the method of injection has been shown to lead to high PM emissions.

Performance improvements

The strategy for engine operation was to run maximum internal EGR at low loads, transitioning to cooled EGR at high loads. The level of cooled EGR varied as a function of speed and load, with the EGR level declining if one desired to increase torque. At high loads the turbocharging requirements of the engine led to a requirement to either reduce EGR flow or accept lower torque levels.

Fuel consumption decreased in the range from 5 percent to 30 percent compared to a typical port-injected engine, depending on the speed load condition examined. For example, the results at light load conditions yielded ~335 g/kWh fuel consumption, which was approximately 8 percent lower than typical engines. At higher loads, where typical engines may be knock-limited, the improvement was better – on the order of 10-15 percent – due to the reduction in knock and improvement in combustion phasing. At high power conditions the improvement was better still, with the elimination of enrichment combining with the reduction in knock to produce up to a 30 percent reduction in fuel consumption.

Conclusion

The results showed that, by adding cooled EGR systems, it is possible to decrease fuel consumption by 5 percent to 30 percent, with the largest improvement occurring in the typical enrichment region. The results also showed that EGR can reduce knock, resulting in improved combustion phasing with a corresponding decrease in fuel consumption and exhaust temperatures. Adding EGR led to lower peak cylinder temperatures and engine heat rejection, resulting in improved thermodynamic efficiency and a reduced heat rejection requirement from the engine block. Finally, the high levels of EGR used in the study reduced CO emissions by 30 percent and NOx by up to 80 percent. The results indicate that adding high levels of EGR to gasoline engines is a very cost-effective way to reduce fuel consumption as well as emissions.

The use of cooled EGR in gasoline engines has been investigated as part of the High-Efficiency, Dilute Gasoline Engine (HEDGE) consortium at SwRI since 2005. A number of auto manufacturers who participated in the HEDGE consortium have adopted this technology for new engine designs.❖

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