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The Effect of EGR on Knock Suppression, Efficiency, and Emissions in a Stoichiometric, Spark Ignited, Natural Gas Engine

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Abstract:
Exhaust gas recirculation (EGR) is widely employed on internal combustion engines for NOx reduction and knock suppression. In this study a comprehensive analysis was performed to determine the effect of EGR on efficiency, emissions, and knock suppression of stoichiometric, spark ignited, natural gas engines. Tests were conducted using a single cylinder, variable compression ratio, cooperative fuel research (CFR) engine at 900 RPM, engine load of 800 kPa indicated mean effective pressure (IMEP), and stoichiometric conditions. The tests were performed using a custom EGR system capable of providing a range of EGR displacement rates from 0% to 40% of the intake charge at engine power levels between 1.5 and 3.5 kW. The experimental measurements included the variance of EGR rate, compression ratio, boost pressure, and location of 50% mass fraction burned (CA50). CA50 was controlled with ignition timing using a Woodward Large Engine Control Module. The use of EGR was found to expand the knock limit, while reducing NOx emissions and increasing engine efficiency as much as 4.5% through increased compression ratio and power density. The highest EGR rate that demonstrated beneficial gains on the CFR engine was 23%; the optimal EGR rate was found to be 19%.

Keywords: Cooperative Fuel Research Engine, Exhaust Gas Recirculation, Stoichiometric Natural Gas, Knocking Threshold

1. Introduction

The large quantity of available natural gas [1] and the significantly lower price of natural gas compared to diesel [2] has resulted in expanded development of natural gas internal combustion (IC) engines, such as those used for municipal truck fleets. Exhaust gas recirculation (EGR) and a 3-way catalyst are typically employed in these applications. EGR has also been implemented as a method of reducing NOx emissions and knock tendencies of internal combustion engines for decades. The application of EGR into stoichiometric, spark ignited, natural gas engines results in lower knock tendency, lower exhaust port temperatures, and reduced engine-out NOx. Knock suppression and lower exhaust port temperatures enable more efficient operation at higher power densities.

Current EGR systems demonstrate maximum EGR rates of 17% on average [3], but this research looks to expand that boundary further and realize additional benefits from the introduction of larger EGR rates. NOx emissions under average EGR rates are lower by approximately one order of magnitude when operating at stoichiometric conditions due to decreased flame temperature and speed [4]. Lower flame speeds result in lower combustion temperatures, longer burn durations, and lower peak pressures. These effects tend to reduce engine efficiency. Operating the engine at higher power densities with EGR recovers efficiency losses, while increasing the EGR rate limit to maintain the benefits of decreased NOx production and knock tendencies [5].

This paper studies the effects of EGR on knock suppression, efficiency, and emissions for a stoichiometric, spark ignited, natural gas engine. Engine tests using the cooperative fuel research (CFR) engine at the Colorado State University Powerhouse and Energy Institute are carried out to explore engine performance improvements due to the effect of EGR. This study also shows the application of EGR to operate within the expanded knock window at or beyond the average knock threshold.

2. Methods / Experimental Set-Up

Tests for this research were performed on a single cylinder, variable compression ratio, cooperative fuel research engine manufactured by Waukesha Motor Company. The CFR engine is a single cylinder research engine with a variable compression ratio capable of sweeping compression ratio from 1:4 to 1:18 while being equipped to run gaseous fuel experiments with fine variable control of engine parameters. This engine was chosen for its versatility and robustness of construction for operating under knocking condition. Figure 1 shows the physical setup of the CFR engine.

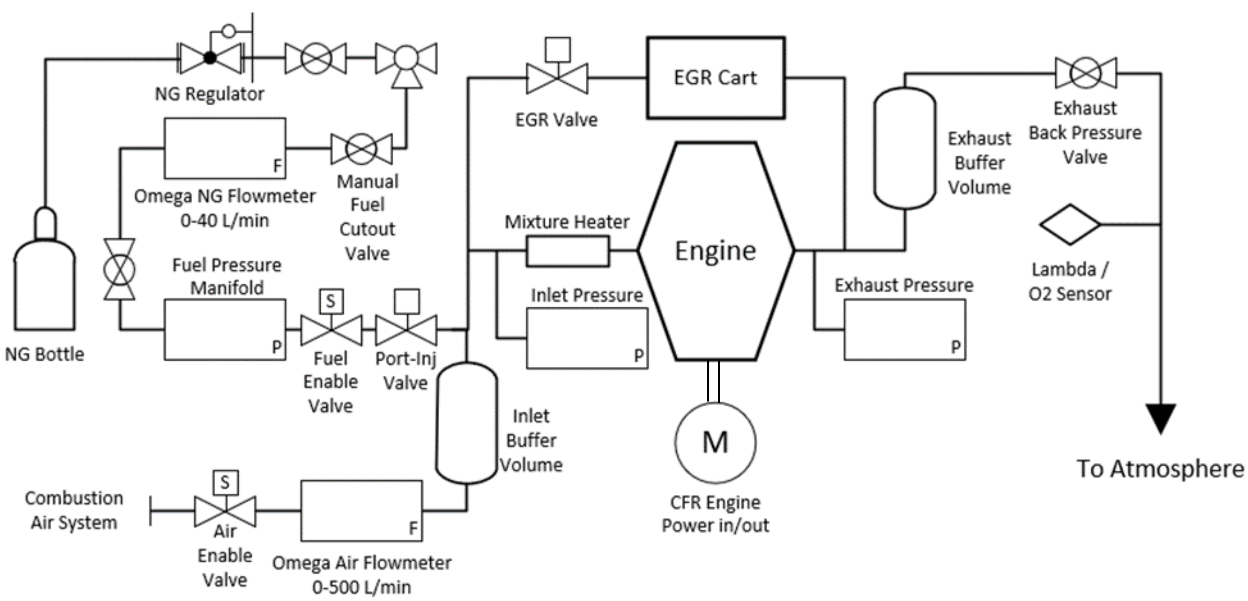

Figure 1: Schematic of CFR Engine System at CSU's Powerhouse and Energy Institute

Many enhancements and alterations had to be made to the CFR engine. Table 1 lists the specification of the CFR engine, and Figure 1 shows a schematic of the engine. The modifications include the installation of a Woodward Large Engine Control Module (LECM), Yaskawa Variable Frequency Drive (VFD), high speed intake and exhaust pressure sensors, Coriolis mass flow meter, and a custom EGR test cart capable of providing variable EGR rates at all engine power levels. CFR engine data was the primary method of determining the effect of EGR on a stoichiometric, spark ignited, natural gas engine.

Engine control and performance analysis was conducted using both a LabVIEW control program and a Woodward LECM combined with all electronic sensors and actuators. The system includes real-time calibration, monitoring, and logging capabilities, and provides control that meets requirements for efficiency, emissions, performance, and reliability. Ignition timing was controlled on the basis of holding 50% mass fraction burned at a set crank angle (CA50), which provides more consistent peak pressure and power output than conventional ignition timing [6].

Table 1: CFR Engine Specifications

Compression Ratio	4 to 18
Bore [cm]	8.26
Stroke [cm]	11.43
Displacement [cm]	611.2
IVO	10° ATDC
IVC	-146° ATDC
EVO	140° ATDC
EVC	15° ATDC
Connecting Rod, Center-To-Center [cm]	25.4
Piston Rings [number]	5
Engine Speed [RPM]	600 to 1200
Timing [ATDC]	-40° to 0°

Sensors monitored flow rate, pressure, and temperature of the working fluid at various regions of the engine. A digital rotary encoder with tenth of a degree resolution was installed on the crankshaft and used to measure crank position for crank angle resolved data. Air and fuel flow were measured using calibrated Omega FMA 1700 series flow meters. Intake charge pressure was measured using a Kistler 4007D high speed piezoresistive pressure transducer. Discharge pressure in the exhaust was then measured with a water cooled Kistler 4049B high speed piezoresistive pressure transducer. Accuracy of these sensors were within 0.05%. Temperatures were measured using Omega type K thermocouples. Emissions concentrations were recorded with a Siemens 5-gas analyzer calibrated for zero reading and for the full span before each test using the respective calibration gases as specified by the manufacturer. Equivalence ratio was measured in the exhaust to verify stoichiometric operating conditions utilizing an ECM Dual-Channel AFRecorder 4800 series Fast Air-Fuel Ratio Analyzer which includes inputs for H/C, O/C, and N/C ratios, improving accuracy for variable fuel composition.

In cylinder pressure was measured using a Kistler 6061B water cooled piezoelectric pressure transducer. The pressure transducer was flush mounted in the cylinder wall, opposite of the side mounted spark plug. A National Instruments PCI 6251 high speed data acquisition card was used to collect in-cylinder pressure data. Data for 1000 engine cycles at 100 kilo-samples/second per channel were recorded for offline analysis.

The EGR test cart is a custom system built to provide the CFR engine with EGR rates from 0% to 40% at all power levels. The system is capable of 400 lpm flow with a VFD controlled twin screw blower. The EGR flow rate is measured with an AGA report #3 standard orifice plate flow meter. The EGR temperature, upstream pressure, and orifice differential pressure are inputs for the EGR mass flow rate calculation. The EGR fluid is extracted from the CFR engine immediately downstream of the CFR engine exhaust port and injected into the intake prior to the mixing of fuel and air. EGR fluid temperature is controlled with an automotive diesel EGR cooler and a 75 Amp tankless water heater. Figure 2 shows the physical EGR test cart.

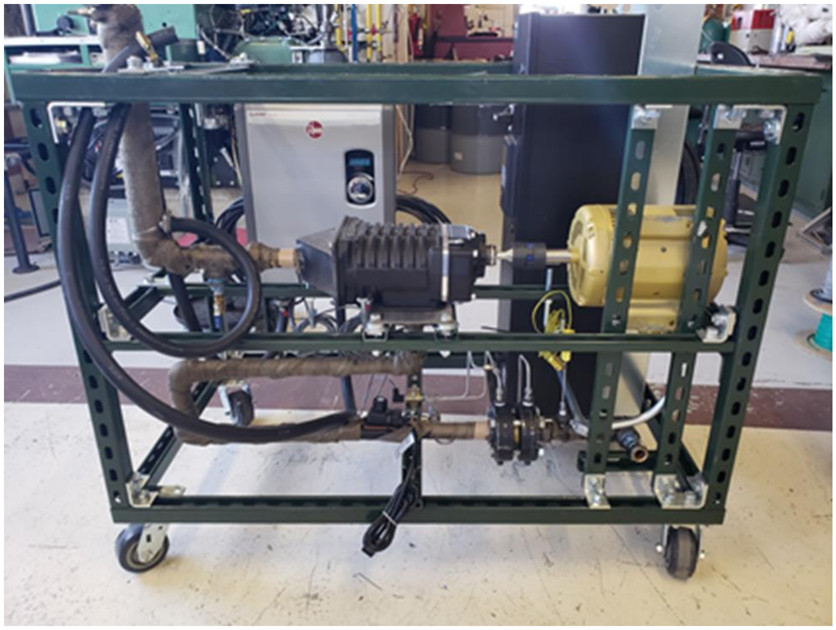

Figure 2: EGR Test Cart for the CFR Engine

The knock threshold was used as a boundary condition for suitable engine operation. The approach taken was to evaluate a Fast Fourier Transform (FFT) of the cylinder pressure to evaluate the dynamics of the pressure trace in the frequency domain [1]. This method is similar in approach to that of Brunt [7] as well as Elmqvist [8] and is evaluated as follows: An FFT function is applied to the cylinder pressure signal in real time with an anticipated knock ripple frequency of 5850 Hz. A band pass filter is applied to the pressure data corresponding to the average engine speed to remove the operating pressure trace and expose pressure data distortions outside of normal operating parameters. When translated to the frequency domain it is possible to detect the ringing corresponding to engine knock. A frequency domain plot of the signal reveals both the frequency at which knock occurs and a magnitude directly corresponding to the energy associated with the knock event. To gather a knock intensity, the magnitudes for 200 consecutive cycles are integrated together and correlated to various levels of auto-ignition. The value used as a boundary condition in this study was a knock intensity equal to or greater than 20.

Table 2: Breakdown of Crucial Variables Within Test Phases

	Compression Ratio	EGR Rate	CA50 Timing	Output Power
Baseline	9.5	0	10.3° ATDC	800 kPa
Phase 1	9.5	0 to 35%	10.3° ATDC	800 kPa
Phase 2	9.5 to XXX	0 to 30 %	10.3° ATDC	800 kPa
Phase 3	Critical CR - 1	0 to 30%	10.3° ATDC	800 to 1250 kPa
Phase 4	Critical CR - 1	15%, 20%	6° to 21° ATDC	100 kPa under critical IMEP

The testing procedure examined the effects of EGR on engine efficiency, combustion knock levels, and emission concentrations for a spark ignited, stoichiometric, natural gas engine. All tests were conducted at a baseline of 900 RPM, 800 kPa IMEP, compression ratio of 9.5, CA50 of 10.3° ATDC, intake temperature of 60° C, and stoichiometric air fuel ratio. The test phases are further explained in Table 2. Equivalence ratio was maintained at 1 ±0.01 for all tests to allow for possibility of catalyst operation. The testing was divided into phases starting with no EGR. The phases included finding the max EGR limit, finding the new critical compression ratio for knock onset, finding the new critical output power for knock onset, and sweeping CA50 ignition timing to discover the max break torque (MBT) timing within the expanded knock threshold. The following data was collected and evaluated for each test condition: in-cylinder pressure, intake and exhaust pressure, intake and exhaust temperature, air flow, fuel flow, ignition timing, engine coolant temperature, lambda value, EGR rate, knock intensity, and emissions concentrations.

3. Results and Discussion

Cylinder pressure traces for tests performed for baseline testing, the addition of 20% EGR, increased compression ratio, and increased power density are shown in Figure 3. The cylinder pressure curves show the average of the 1000 cycles. With the addition of EGR, in order to maintain the same output power at constant equivalence ratio, the boost pressure must raise and thus peak pressure climbs, as well as the rate of pressure rise. These changes also affect the frequency of irregular combustion and misfire, which becomes the limiting factors in engine operation.

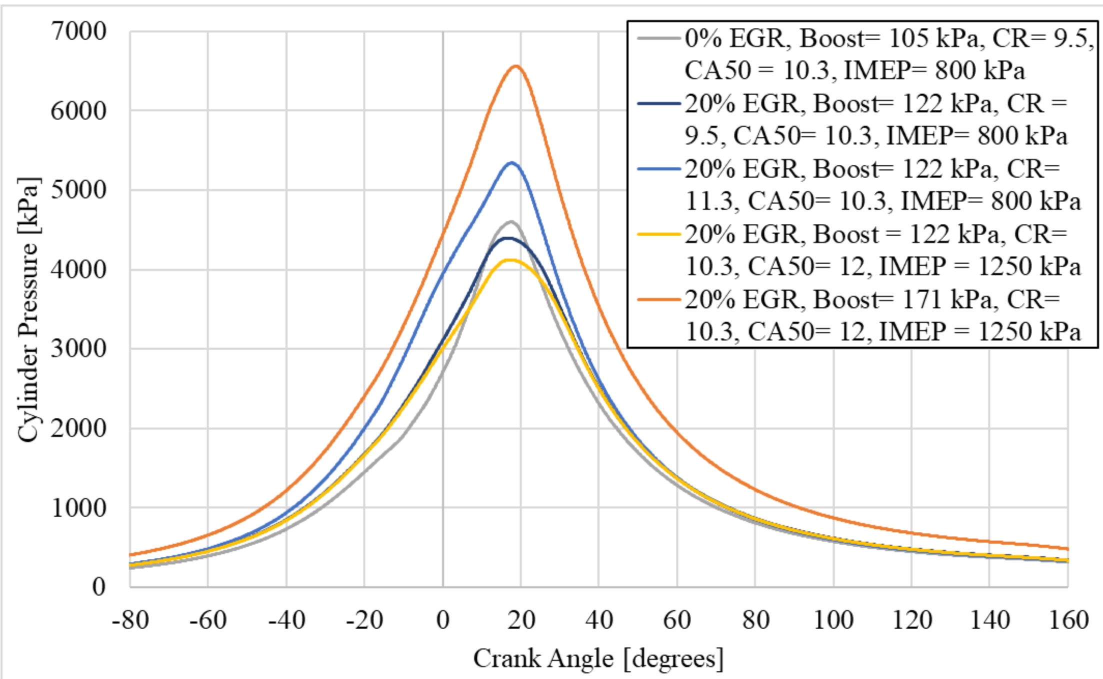

Figure 3: Average In-Cylinder Pressure Traces from Each Testing Phase

For comparison, Figure 4 shows the cylinder pressure curves from a 0% to 35% EGR sweep. It is visible that as EGR is added the combustion duration is increased and greater cycle variations are observed in IMEP, peak pressure, and knock tendencies. All data points beyond 25% EGR rate are well below combustion stability limits.

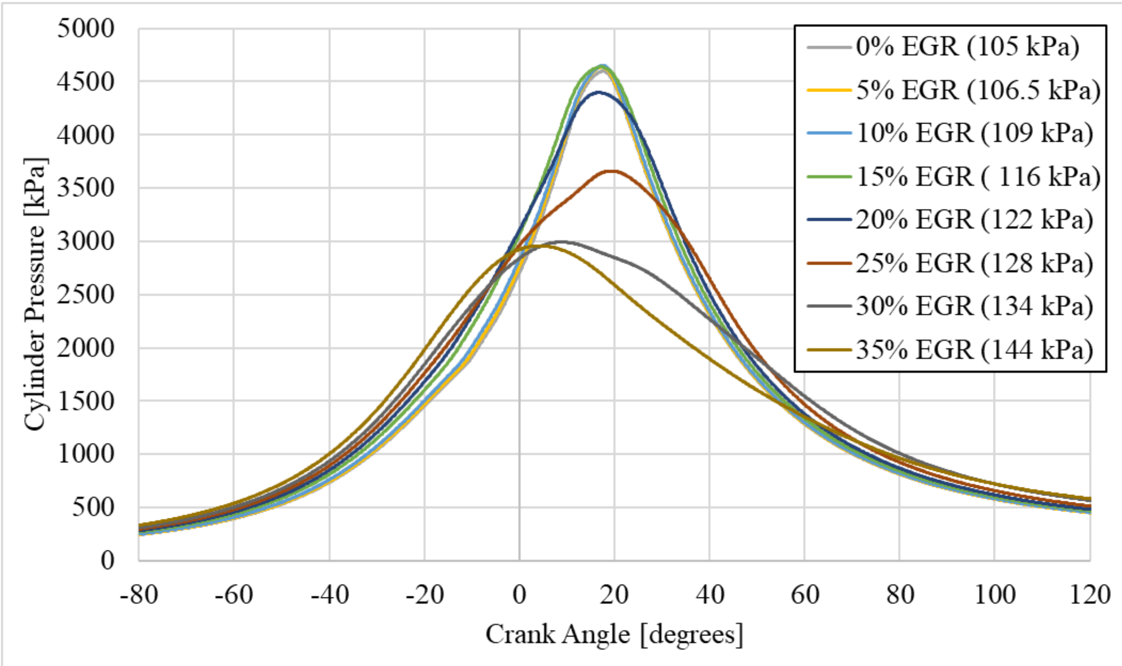

Figure 4: In-cylinder Pressure Traces for 0-35% EGR Rate Sweep (CR = 9.5, CA50 = 10.3° ATDC, IMEP = 800 kPa)

The coefficient of variance (COV) of peak pressure is plotted with efficiency versus increasing EGR rate in Figure 5. The COV of peak pressure provides a measure of combustion instability. A high COV of peak pressure signifies a highly variable pressure trace, and thus a highly variable output power. This is primarily a result of misfire, incomplete combustion, and increased burn duration with high EGR rates. A maximum COV of peak pressure occurs at 26% EGR, with all data points at higher EGR rates demonstrating a decreasing COV of peak pressure due to the large percentage of misfiring cycles. Higher levels of EGR demonstrated lower combustion stability due to the higher concentrations of misfires in a spark ignited engine. The brake efficiency increases until 20% EGR due to lower combustion temperatures and thus lower mixture specific heat. At 20% EGR, the COV of peak pressure experiences a positive inflection point where it increases rapidly, and efficiency begins to degrade. EGR rates above 25% demonstrated efficiencies lower than engine operation with 0% EGR due to persistence of misfires, incomplete combustion, and longer combustion durations [9].

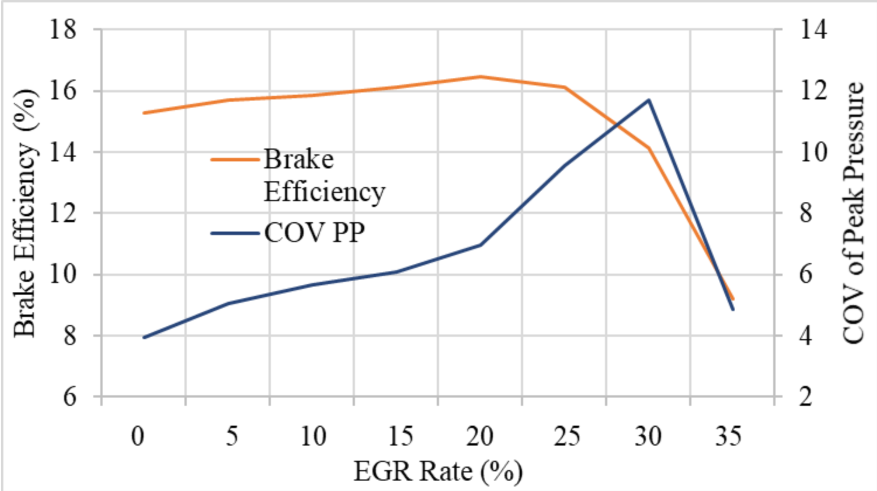

Figure 5: COV of Peak Pressure vs Efficiency for 0-35% EGR

The combustion phasing in this work is determined from the mass fraction burned (MFB) calculation derived from the cylinder pressure-based heat release rate. The heat release rate is integrated with respect to crank angle to give the heat release which is divided by the fuel energy per cycle to give the MFB. In computing the MFB curves the cycle average in cylinder pressure was used.

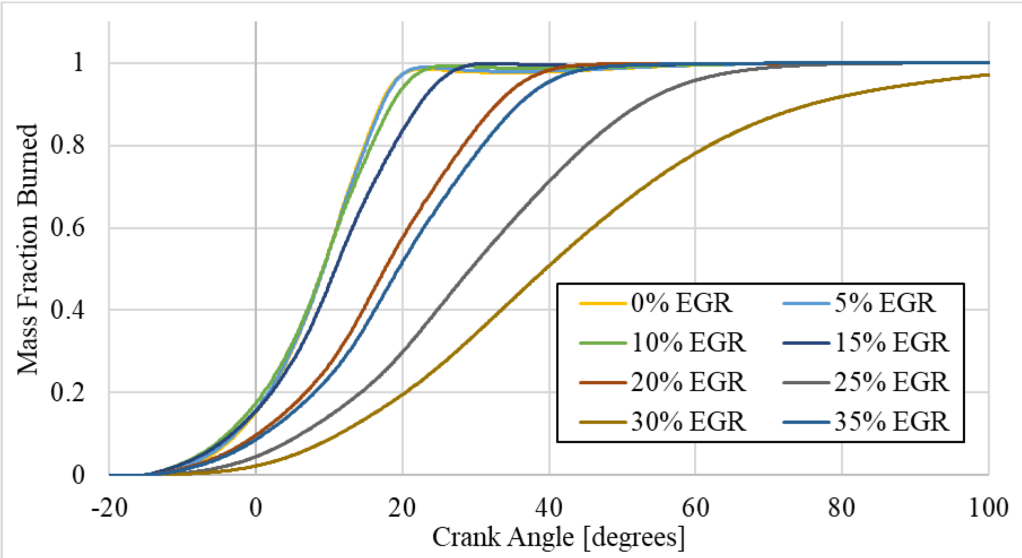

Figure 6: Mass Fraction Burned for 0-35% EGR

The total heat release curves are calculated for 0% to 35% EGR and are plotted against crank angle in Figure 6. This figure shows that for 0% EGR, 90% of the MFB occurred before 20° ATDC. The burn duration increased by four times in duration at 35% EGR as compared to 0% EGR conditions. As an indicator of how close the 0% EGR rate is to constant volume combustions, the volume change during the 7° of crank rotation from 0% EGR is less than 0.5% of the displacement volume. If this 7° of change is centered on top dead center (TDC), it is even smaller and less than 0.3% of the displacement volume. In comparison the 21° of change for the 35% EGR case is 4% of the displacement volume under the same phasing conditions. A stable

MFB rate that doesn't exhibit significantly long burn durations occurs between 15% and 20% EGR. For a gasoline fueled SI engine with spark timing optimized for maximum efficiency, combustion starts 10° to 40° BTDC, is half completed around 10° ATDC, and ends (90% MFB) around 30° to 40° ATDC [6].

Figure 7 show the ignition delays (0-10% burn) and burn durations (10-90% burn) in crank angle degrees plotted against EGR percentage respectively. These plots demonstrate trends of increasing ignition delay and burn duration with increasing EGR rate by a factor of 2 per 5% EGR rate additions. Increasing the EGR rate and decreasing in compression ratio both cause a decrease in combustion temperature. These variables cause a reduction in laminar flame speed, thus increasing both ignition delay and burn duration. Examining the effect on ignition delay at 0% EGR further in figure 7, it is seen that the durations are between 19° and 24° for this range of operating conditions. When 35% EGR is added the ignition delay becomes 31°, showing 2.5 times increase in duration over the 35%. Similar trends in the 10-90% burn duration are observed. An increase in EGR and a decrease in compression ratio cause an increase in burn durations. The addition of EGR from 0% to 35% EGR cause an increase in burn duration from 19° to 58°.

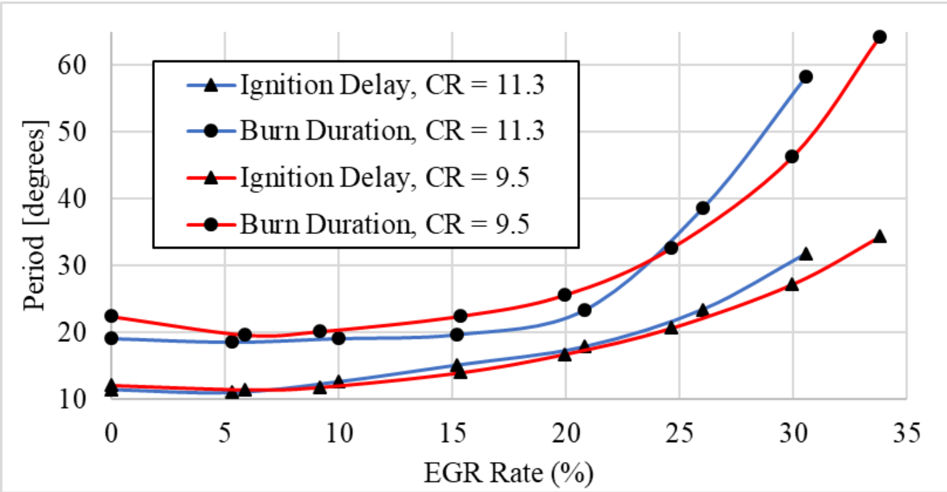

Figure 7: 0-10% and 10-90% MFB vs EGR Rate

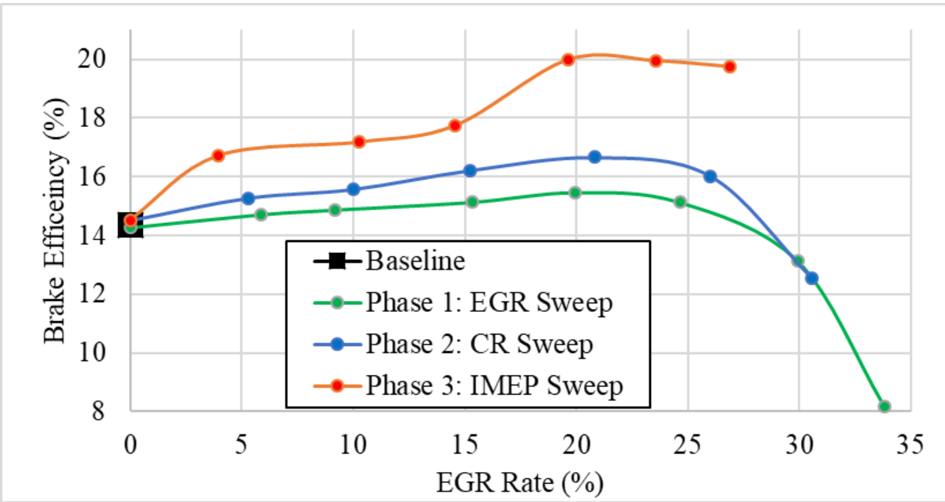

Figure 8: Brake Efficiency vs EGR Rate

Figure 8 shows the brake efficiencies for 0-35% EGR for baseline, critical compression ratio, critical output power, and the new max brake torque (MBT) CA50 ignition timing optimization test phases. Values and curves for EGR rates from 0-35% are plotted. The critical compression ratio increases by 18%, the critical power output increases by 46%, and the location for MBT CA50 ignition timing shifts to more advances timings for increased EGR rates. The conditions for maximum efficiency occurs one CR unit below the critical compression ratio, and 20 to 30 kPa IMEP below critical output power while operating at MBT CA50 ignition.

Figure 9 shows the maximum efficiency from each engine variable optimization. The largest efficiency gain occurred due to increasing the critical output power with EGR which saw an efficiency gain of 4.5% absolute and 23% relative. The largest efficiency gain within an optimization step was 2.1% absolute and 11% relative at 20% EGR rate due to increasing output power to a critical knock level. Combustion phasing is closely related to engine efficiency and CA50 ignition timing provides a better indication of combustion phasing than ignition timing. Results show that despite the increase in ignition delay and burn duration, non-knock limited data points exhibit similar locations of burn completion compared to gasoline SI engines, despite the large difference in combustion durations.

For higher compression ratios (10 and above) with EGR rates below 10%, the peak efficiency is knock limited. For all test phases, efficiency increases until 20% EGR as engine operation moves away from knock limits but below misfire limits. The large increase in burn duration within combustion phasing can also be attributed to lower efficiencies below 20% EGR. This also leads to the reduction in flame speed and thus a lack of proper combustion timing.

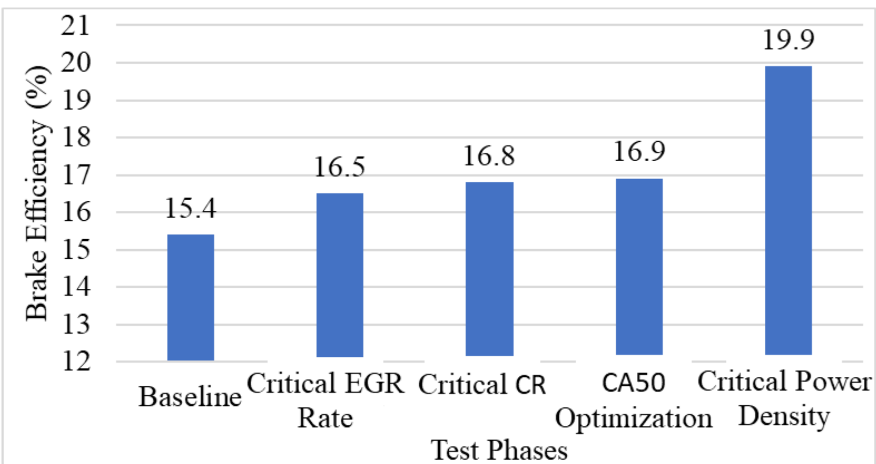

Figure 9: Max Efficiency Values from Each Engine Optimization Phase

4. Conclusions

In this study, EGR was applied to a CFR engine to study the impact of EGR on stoichiometric, spark ignited, natural gas engines. This was implemented using a custom EGR cart that controlled the EGR rate independent of engine conditions. Engine efficiency and combustion statistics were utilized to evaluate performance.

The addition of EGR to baseline CFR operating points, initially increased efficiency until 26% EGR rate, and then decreased efficiency values for any greater EGR rate. The knock intensity values decreased with increasing EGR rates, allowing for the knock threshold to be expanded in an identical function. Operating at higher critical compression values compared to that of 0% EGR allowed for a 3.4% efficiency gain. Then operating at the new critical output power of 1250 kPa

IMEP instead of 800 kPa allowed for a 4.5 % efficiency gain at 22% EGR rate. For all tests, any EGR rate over 22% started a degradation of both efficiency and combustion with any test point over 26% EGR demonstrating lower efficiencies than baseline testing.

The prime operational window for a spark ignited, stoichiometric, natural gas engine with EGR was found to be between 15% and 20% EGR rate with a compression ratio around 10.5, depending on the run conditions of the engine. Further benefits were proven to be reached, if the engine allows for operation beyond the onset auto-ignition. The addition of EGR shifted the MBT CA50 spark timing value from 10.3° ATDC to 11.9° ATDC, due to the increase in ignition delay and burn duration by 22° and 41°, respectively.

5. Acknowledgements

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