Experimental Investigation of Sources of Influence of Exhaust Gas Recirculation on the Spark Ignition Combustion

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Introduction

• This work represents part of the PhD thesis:

Influence of the Exhaust Gas Recirculation on the Occurrence of Knock in Modern SI Engines

Exhaust Gas Recirculation (EGR) is a nitrogen oxide (NO\textsubscript{x}) emissions reduction technique used in SI engines. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. This dilutes the O\textsubscript{2} in the incoming air stream and provides gases inert to combustion to act as absorbents of combustion heat to reduce peak in-cylinder temperatures.

Knock occurrence – abnormal combustion
Experimental IC Engine setup

Control room
Experimental IC Engine

Manufacturer: Hatz, 1D81Z

Engine type: 1 cylinder, 4 stroke

Combustion chamber: Toroidal

Intake Valve Timing: Open @ 340°, Close @ 590°

Exhaust Valve Timing: Open @ 154°, Close @ 380°

Bore, mm: 100

Stroke, mm: 85

Compression ratio: 12

Displacement, ccm: 667.59
Experimental IC Engine Testbed

Control cabinet

- Air Heater
- AC Dyno
- IC Engine
- Fuel mass
- cDAQ
- Spark
- Injector
- cRIO
- Power supply
- Throttle

Testbed

- Intake
- Exhaust
- EGR

Experimental Engine

10/3/2017
Experimental IC Engine setup
Acquisition and processing of fast crank-angle based signals typical for combustion engines.
Knock in IC SI Engine (Internal Combustion Spark Ignition) is induced by:

- High compression ratio
- Low octane number
- Large flame propagation path
- Spark advance
- Boosting of the engine
- Large engine load
- Low cooling of the combustion chamber
Experiment

The main factors that influence knock suppression are:

- Flame propagation speed,
- Chemical influence on auto ignition ($\text{CO}_2$, $\text{H}_2\text{O}$, dilution etc.),
- End-gas temperature influence.

Experimental study with four cases:

- **First**: normal operating condition of engine without the application of EGR.
- **Second**: cooled EGR is applied.
- **Third**: cooled EGR is applied with same intake temp as 1st case
- **Fourth**: application of the EGR and higher intake air temperature obtained with air heater.
Higher intake temperature is applied in order to equalize the maximum temperature of the end-gas obtained in first case (the case without EGR) in order to determine the temperature influence on knock suppression.

EGR dilution applied - reduced the energy supplied to the cylinder. Intake temperature increase - reduced intake charge density.

Compensated by the optimization of the intake pressure.

Resulting in constant energy flow for all operating points:

**Air 22.3 kg/h**

**Fuel 1.5 kg/h**

**EoF = 1432 J/cycle**
Selection of data acquired

- End-gas peak temperature, K
- CA50, °CA ATDC

Data points:
- 0% EGR
- 15% EGR
- 15% EGR; AH; ST -20
- 15% EGR; AH; ST -18
- 15% EGR; AH; ST -16
- 15% EGR; AH; ST -14
- 15% EGR; AH; 22 °C
- 15% EGR; AH; 22 °C 2nd
- 15% EGR; AH mix

Note: 890 K and 20.7 °CA are highlighted on the graph.
Same end-gas temperature show the same tendency to knock regardless of EGR dilution implemented.

Maximum amplitude of pressure oscillation (MAPO) index for 300 cycles was taken into consideration.

For the group B, the number of cycles with MAPO > 0.5 bar were counted in order to show the knock tendency.
End-gas Temp. and ROHR
Group A

Anomalies caused by knock combustion cycles

Max end-gas temperature

Earlier combustion phasing

Longer combustion duration

Case three with EGR dilution implemented was able to achieve advanced combustion phasing with the same knock intensity, it resulted with higher IMEP than cases one and four.
End-gas Temp. and ROHR
Group B

- case **four** at the limit of knock combustion
- higher intake temperature influences the end-gas temperature and lowers the knock resistance

- application of EGR decrease the ROHR, lowers end-gas temp. and increase burn duration. (+IMEP)
- Higher end-gas temp. increase ROHR
Application of EGR dilution significantly reduces NO\textsubscript{X} emission.

<table>
<thead>
<tr>
<th>Operating point, No</th>
<th>NO\textsubscript{X} (g/kWh)</th>
</tr>
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<tbody>
<tr>
<td>C1.1</td>
<td>12</td>
</tr>
<tr>
<td>C3.1</td>
<td>10</td>
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<td>C4.1</td>
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<tr>
<td>C1.3</td>
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</tbody>
</table>

Lower availability of oxygen in cases with EGR.

Variable end-gas temperature.

Similar end-gas temperature.

Earlier combustion phasing.

Literature research indicates that a certain amount of NO\textsubscript{X} in the intake (recirculated via EGR) can increase engine knock tendency.

Reduced end-gas temperature had greater influence on knock suppression than NO\textsubscript{X} on the increase of knock tendency.
Conclusion

• With the use of EGR abnormal combustion was effectively suppressed.

• The operating points with EGR and with lower intake temperature suppress knock by lowering the end-gas temperature.

• If the temperature of the end-gas is constant the tendency to knock is at the similar level regardless of other operating conditions for the same level of EGR.

• The temperature effect of EGR dilution has significant influence on combustion and knock tendency in comparison to other influences of EGR, e.g. flame speed and chemical effects.

• Application of EGR dilution reduces NO\textsubscript{X} emission significantly.

According to the results of this study, the impact of the exhaust gas recirculation on charge temperature and consequently on tendency of engine to knock and has high influence on lowering of fuel consumption. Also the charge temperature effect of EGR has significant impact on NO\textsubscript{X} formation. Therefore the use of EGR has significant impact on the sustainability of the SI engines.
Thank you for your attention!
Questions, comments, ...

Acknowledgment
The study was performed within the FMENA project “Experimental Research, Optimization and Characterization of piston engine operation with DUal-Fuel COmbustion - DUFC OROC” IP-2014-09-1089 funded by the Croatian Science Foundation. This help is gratefully appreciated. [www.fsb.unizg.hr/miv/dufc/oroc](http://www.fsb.unizg.hr/miv/dufc/oroc)
Introduction

Limitations:

RPM - Engine Speed
EGR - Exhaust Gas Recirculation
p - In-Cylinder pressure
LTHR - Low Temperature Heat Release
\vartheta - In-Cylinder temperature
\varepsilon - Compression ratio
Heat release calculation

First law of thermodynamics

\[ \Delta U = Q - W \]
\[ dU = dQ - dW \]
\[ dQ = dU + dW \]

**Heat**

\[ dQ = dQ_{hr} - dQ_{ht} - dQ_{cr} - dQ_{BL} \]

**Internal Energy**

\[ dU = \frac{C_v}{R} (Vdp + pdV) \]

**Work**

\[ dW = pdV \]

**Heat release per crank angle**

\[ \frac{dQ_{hr}}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} + \frac{dQ_{ht}}{d\theta} + \frac{dQ_{cr}}{d\theta} \]

Experimental setup = pressure and volume as a function of crank angle

Source: Bengt Johansson

“Heat release analysis”