Internal Combustion Engines – MAK 493E

EXHAUST PROCESS and EMISSIONS

Prof.Dr. Cem Soruşbay
Istanbul Technical University

Exhaust Process in Engines and Emissions
- Introduction
- Exhaust process phases
- Gas flow rate and temperature variation
- Exhaust emissions
Introduction

After combustion is completed and resulting high pressure gases have been used to transfer work to crankshaft during expansion stroke, these gases are removed from the cylinder in two steps: exhaust blowdown which is followed by exhaust stroke.

valve overlap

The resulting flow in the exhaust pipe is a non-steady state pulsating flow.
Introduction

Blowdown phase
when exhaust valve opens towards the end of power stroke (60 – 40° BBDC) cylinder pressure is about 0.4 – 0.5 MPa and temperature up to 1000 K, while pressure in exhaust system is one atm.

pressure difference causes rapid flow of exhaust gases from cylinder – blowdown phase.

flow at first is choked and outflow will be sonic

With increasing engine speed, crank angle duration of blowdown phase increases

Introduction

Displacement phase (exhaust stroke)
mass flow is controled by piston movement from BDC to TDC pressure is slightly above atm pressure

closing of the valve starts at or close to TDC and the total closing is at 8 – 50 ° ATDC

Valve overlap
intake valve starts to open 10 – 25 ° BTDC
valve overlap 15 – 50 ° CA

there can be reverse flow into cylinder :
inc residual gases, which is worst at low speeds and idle
short circuit of intake air/fuel mixture – inc pollution
Temperatures

**SI engines**
- exhaust gas temp: 400 – 600 °C average
- 300 – 400 °C at idle and 900 °C at max power

when exhaust valve opens, in cylinder gas temperature is
- 200 – 300 °C more

**CI engines**
- 200 – 500 °C average

cooling occurs due to larger expansion in Diesel engines

Pollutant Formation

IC – engine exhaust gases contain oxides of nitrogen (NO and some amounts of NO2 – collectively known as NOx), carbon monoxide (CO) and unburned hydrocarbons (HC).

Soot and PM in Diesel engines.

The amounts depend on engine design and operating conditions.

These pollutants are measured as concentrations;
- CO, CO₂, O₂ as vol. [%]
- NO, NO₂, NOₓ as [ppm] (parts per million)
- HC as [ppm] or [ppm C]

eg 1 ppm propan, C₃H₈
    3 ppm C
Control of Pollutant Emissions

Combustion related applications:
- EGR (Exhaust gas recirculation)
- Water and alcohol injection

Exhaust gas treatment:
- Thermal reactors
- Catalytic converters
- Traps and filters
### EGR control

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<thead>
<tr>
<th>1</th>
<th>2</th>
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<tbody>
<tr>
<td>Spark advance</td>
<td>Dwell angle</td>
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<thead>
<tr>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>Full load</td>
<td>Opening ratio</td>
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<tr>
<td>Part load</td>
<td>Engine speed</td>
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<tr>
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<th>6</th>
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<tr>
<td>EGR valve position</td>
<td>Acceleration enrichment</td>
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### Exhaust Gas Treatment

**Thermal reactors**

Require high temperatures, oxygen availability, sufficient time for reactions.

Used for oxidation of CO and HC

- Rich mixture + O2 supplement: CO oxidation in exhaust system increases T, but fuel consumption also increases.

- Lean mixture + late ignition: high exhaust temperatures, but loss in power output
Exhaust Gas Treatment

Catalytic converters

Oxidizing catalysts for HC and CO

Reducing catalysts for NOx

Three-way catalysts for all three pollutants
Catalytic Converters

Catalytic Converters
Catalytic Converters

Exhaust Gas Treatment

\[ C_m H_n + \left[ m + \frac{n}{4} \right] O_2 \rightarrow m \text{CO}_2 + \frac{n}{2} \text{H}_2 \text{O} \]  
\[ \text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 \]  
\[ \text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2 \text{O} \]  
\[ \text{CO} + \text{NO} \rightarrow \frac{1}{2} \text{N}_2 + \text{CO}_2 \]  
\[ C_m H_n + 2 \left[ m + \frac{n}{4} \right] \text{NO} \rightarrow \left[ m + \frac{n}{4} \right] \text{N}_2 + \frac{n}{2} \text{H}_2 \text{O} + m \text{CO}_2 \]  
\[ \text{H}_2 + \text{NO} \rightarrow \frac{1}{2} \text{N}_2 + \text{H}_2 \text{O} \]  
\[ \text{SO}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{SO}_3 \]  
\[ \frac{5}{2} \text{H}_2 + \text{NO} \rightarrow \text{NH}_3 + \text{H}_2 \text{O} \]  
\[ \text{SO}_2 + 3 \text{H}_2 \rightarrow \text{H}_2 \text{S} + 2 \text{H}_2 \text{O} \]  
\[ \text{NH}_3 + \text{CH}_4 \rightarrow \text{HCN} + 3 \text{H}_2 \]  
\[ \text{CO} + \text{H}_2 \text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]  
\[ \text{CH}_n + 2 \text{H}_2 \text{O} \rightarrow \text{CO}_2 + [2+n/2] \text{H}_2 \]
Exhaust Gas Treatment

\[
\begin{align*}
\text{CO} + \frac{1}{2} \text{O}_2 & \rightarrow \text{CO}_2 & (2) \\
\text{CO} + \text{NO} & \rightarrow \frac{1}{2} \text{N}_2 + \text{CO}_2 & (4)
\end{align*}
\]

In lean mixtures reaction (2) is dominant – O2 is present. CO is reduced by oxidation and insufficient CO for the relatively slow reaction (4).

\[
\begin{align*}
\text{CO} + \text{H}_2\text{O} & \rightarrow \text{CO}_2 + \text{H}_2 & (11) \\
\text{CH}_n + 2 \text{H}_2\text{O} & \rightarrow \text{CO}_2 + [2+n/2] \text{H}_2 & (12)
\end{align*}
\]

In rich mixtures reactions (11) and (12) have to be faster.

Exhaust Gas Treatment
Emission Regulations – Road Simulations

Emission Regulations – Exhaust Gas Emissions
Emission Regulations – Chasis Dynamometers
Emission Regulations – Chasis Dynamometer

Emission Regulations – Exhaust Gas Emissions