CONTENT:

- The Indicating Measuring Chain
- Basics of Indicating and Parameters
- Indicating for Emission Reduction
- Contribution of Optical Measurement Tools
- AVL Combustion Measurement - Product overview
- Application Examples
INDICATING AND COMBUSTION ANALYSIS
How we notice combustion?

Amplifier
- Charge Amplifier

Crank Angle Signal
- Crank Angle Encoder

Cylinder Pressure
- High Pressure Sensor (piezo electric)

High Speed Data Acquisition
- Indicating System

Data Acquisition SW
- Control of HW
- Calculation / Analysis

Post Data Processing
- Post Data Processing Tool

Meaningful Measurement Results require
... accurate Measurement tools
INDICATING AND COMBUSTION ANALYSIS
How we notice combustion?

Typical measurements
- Cylinder pressure
- Degree Crank Angle – crank angle encoder / calculator
- Low Pressure measurement in intake and exhaust manifold
- Line Pressure Sensors (max. 3000 bar)
- TDC Sensor - Top dead center sensor
- Turbo Speed Sensor
- Needle Lift Sensor / Valve Lift Sensor
- Ignition / Injection Timing
- . . .
indicating parameters

- imep – indicated mean effective pressure
- maximum pressure; $p_{\text{max}}$
- angle of maximum pressure
- maximum pressure rise
- 50% heat release angle
- start and end of combustion
- cyclic variation of above values (statistics)
- cylinder distribution of above values (statistics)

pressure measurement for thermodynamic analysis: power, heat, energy balance
STANDARD EVALUATION OF THE CYLINDER PRESSURE

![Graph showing cylinder pressure, needle lift, combustion chamber pressure, and injection line pressure over degrees CA.](graph.png)
THERMODYNAMIC RESULT VALUES

Measurement / Calculation Values

Rate of heat release - kJ/m³ grd deg

Mass fraction burnt - %

Center of gravity of combustion

Angle of Integral Heat

α 5% Start of combustion

α 50% Main burning activity

α 95% End of combustion

Result Values
STATISTICAL EVALUATION OF CYLINDER PRESSURE SIGNALS

**Measurement**

- Cylinder pressure vs. deg CA

**Result values**

- IMEP vs. α_max
- Cycle count

**Statistics**

- Maximum: \( p_i^{\text{max}} \)
- Mean value: \( p_i^{\text{Mean}} \)
- Minimum: \( p_i^{\text{min}} \)
- Coefficient of variance: \( V_{p_i} \)
ENGINE DEVELOPMENT CYCLE

steps in development

pre-series certification
endurance test test bed and vehicle calibration on vehicle
development and calibration on test bed research

% Time
0 50 100
LINK BETWEEN COMBUSTION AND EMISSION

- misfiring ➢ HC
- knock ➢ NOx
- steep temp / pressure rise ➢ NOx
- too early combustion ➢ NOx
- too late combustion ➢ HC, PM, soot
- partial combustion ➢ HC, PM, soot
  (wall film, condensation/cold components, over fueling, fat mixture, improper spray / geometry, … )

NOx ➢ temp reduction - EGR
PM, soot ➢ premixed flame
HC ➢ no unburnt fuel, stable combustion
INFLUENCE OF COMBUSTION ON EMISSIONS

Rate of Heat Release

**stiff combustion**
- high NOx
- high noise

**soft combustion**
- low NOx
- low noise
- increased soot
- high HC
COMBUSTION TIMING AND EMISSIONS

SOI = start of injection

Emission

% 260 220 180 140

deg CA - 4 - 3 - 2 - 1 0 1 2 3 4 5 6 advanced lowest SFC retarded

α

HC

NOx

lowest SFC
INFLUENCE OF INJECTION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NOₓ</th>
<th>HC</th>
<th>PM</th>
<th>Power/Torque</th>
<th>Noise</th>
<th>Appl. Effort</th>
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</thead>
<tbody>
<tr>
<td>High Injection Pressure</td>
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<tr>
<td>Late Start of Injection</td>
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<td>Pilot Injection</td>
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<td>Injection Rate Control</td>
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<td>Nozzle Hole Quality</td>
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<tr>
<td>Post Injection</td>
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</tbody>
</table>

Positive Effect: Green Arrow
Negative Effect: Red Arrow
Limitation of Information derived from Combustion Pressure

- Flame quality – can not be evaluated
- Emissions are directly linked to flame quality

Flame quality can be studied in detail with optical methods giving a deeper understanding of the actual combustion.

Optical methods are grown up – they are no longer a scientific tool for R&D only

- Tailored test bed solutions for typical problems are available
INDICATING AND COMBUSTION DEVELOPMENT TOOLS - VISIOSCOPE

VISIOSCOPE

- live pictures with full geometry information or temperature information
- only one picture per cycle
**INDICATING AND COMBUSTION DEVELOPMENT TOOLS - VISIOLUTION**

**VISIOLUTION**

- **advantage:**
  - good information over entire cylinder cross section with highest CA resolution

- **disadvantage:**
  - lower spatial resolution

- up to 40 channels
INDICATING AND COMBUSTION DEVELOPMENT TOOLS - VISIOSET

VISIOSET

advantage:
- rough information over entire cylinder cross section and good information on flame around spark plug with highest CA resolution

disadvantage:
- lowest spatial resolution

➢ up to 8 channels
Stoichiometric, premixed flame in warm engine:
all fuel evaporated and mixed with air

Flame radiation is synchronous with combustion pressure

Stationary part load, benchmark example

VisoFlame
Spark Plug Probe
Premixed flame starts at spark plug and ignites wet surfaces fuel

Premixed flame radiation, then ongoing surface diffusion flame radiation

Premixed flame not seen in photograph because of low intensity flame radiation. Very bright diffusion flame

Photograph by Witze, Green, Sandia

Optical Measurements – Sooting Flame

Early starting cycle in cold engine

Premixed flame burning volume charge yields combustion pressure
Mixture conditions at cold start.  
Schematic by Toyota, SAE 950074

**Ignition:** little fuel vapor near spark plug causes small flame

- **Premixed combustion:** pressure rise as volume charge burns
- **Liquid film combustion:** very bright flame, but low rate of heat release

Ignition phase disturbed by overfuelling, fuel droplets hitting the flame kernel.
advantage:
- cheapest optical system
- excellent for transient soot measurements

disadvantage:
- only one conical segment can be viewed

- 2 channels
Urgent statement of a leading diesel car producer: “Our CR injection systems operated in stationary engine tests we manage to optimise for low soot and NO\textsubscript{x}. But we do not understand how to optimise CR in transient mode! How much pilot, pre-main-post injection? How many crank angle degrees in between? How do we adapt to changing load, boost pressure, residual gas?

We need a real time, crank angle resolved transient data acquisition for soot and NO\textsubscript{x}.”

VISIOFEM

optical amplifier

600nm  950nm

fibre optics cable

optical sensor in glow plug adapter
HOW TO READ THE DATA?

... we get traces of
- injection
- cylinder pressure
- flame intensity

flame intensity
- amount of soot
- two-colour flame evaluation
- temperature / NOx

trend verification with
Filter Smoke Number (FSN)

= f (EOI)
Combustion analysis with pressure transducers is a very powerful tool for engine improvement with some simple algorithm the trend in emissions, noise or fuel consumption can be easily assessed before going to detailed emission analysis the extend of improvement can be already assessed also by means of optical measurement tools.
AVL COMBUSTION MEASUREMENT

Product Overview

Alfred Kristoferitsch
Combustion Measurement
AVL Graz
Product Overview

**Sensors**
- Pressure Sensors
- Crank Angle Encoder

**Indicating Systems**
- System Overview
- IndiCom

**Amplifier**
- Charge Amplifier
- Amplifier with more functions

**Post Data Processing**
- AVL CONCERTO
**SENSORS**
Combustion Pressure – **AVL GaPO$_4$**

- **High thermal stability:**
  - temperature consistent up to 970°C
  - no twin growth (compared to quartz)

- **High piezoelectric sensitivity:**
  - high sensitivity in small sensors as well (GU21C 35pC/bar)
  - excellent distance between signal and noise

- **No thermal sensitivity change**
  - assumption for correct measuring results under all load point (typical sensitivity change for AVL GU12P between 20°C - 400°C : +0,5% / -0,2%)
SENSORS
Combustion Pressure AVL - GaPO$_4$

- Direct mounted
  - preferred solution for highest accuracy
  - ideal mounting position possible

- Spark Plug
  - no additional bore in cylinder head required
  - wide range customer spark plugs available
  - sensor is as close as possible to the combustion chamber – high accuracy / no pipe oscillation

- Glow plug
  - no additional bore in cylinder head required
  - sensor is as close as possible to the combustion chamber – high accuracy / no pipe oscillation
SENSORS
Crank angle based measurement – optical sensor

- **AVL Chrank Angle Encoder 365C**
  - standard combustion engines
  - optical measurement principle
  - for mounting a free shaft end or belt pulley is required

- **AVL Chrank Angle Encoder 365X**
  - open disc
  - used for mounting situations without free shaft end, e.g. on drive side

- **AVL Chrank Angle Encoder 365R**
  - designed for racing application
SENSORS
Further sensors available:

- Low Pressure Sensor
  - Pressure measurement in Intake and exhaust manifold
- Line Pressure Sensors
  - up to 3000 bar line pressure
- TDC Sensor
  - Top dead center sensor
- Turbo Speed Sensor
  - Laser sensor
- Needle Lift Sensor
- Valve Lift Sensor
AVL Amplifier Product Portfolio

**MicroIFEM**
- MicroIFEM - 4 Channel amplifier
  - 4 Ch. Piezo
  - 4 Ch. Multi Purpose (MP)
  - 2 Ch. Piezo / 2 Ch. MP

**FlexIFEM**
- FlexIFEM – 1/2 Channel amplifier
  - 1/2 Ch. Piezo
  - *MP available 2010*
LCD Display
- Visualizes operation menu
- User-friendly setting of parameters
- Displays results or pressure curve

Calculation
- Provides cycle by cycle calculations
- Peak cylinder pressure $p_{\text{max}}$
- Engine speed
- Output of warning and alarm levels

FlexIFEM Advanced
- Combustion Noise function
- Knocking (not yet available)
FLEXIFEM Advanced – Combustion Noise Meter

- Stand alone charge amplifier with integrated combustion noise function
- Comparability to
  - Analog AVL 4050 Combustion noise meter
  - AVL combustion noise function in IndiCom
- Download your own transfer (MFFR) curve
- Updates via software
- Further algorithms planned: e.g. AVL CKI
AVL INDICATING SYSTEMS
LIGHT LINE

IndiModul Start

IndiSmart
Including Charge Amplifier

NEW

• Cost-Effective Solution for Standard Indicating applications

• Light System with full upgradeability to Advanced Indicating System

• Ideal for combustion investigation on 4-6 cylinder engines

• Easy-to-use IndiCom Light Interface

• 0.1 deg. CA measurement resolution up to 11000 rpm with max. 1530 measuring points per cycle

• IEEE1394 Firewire interface
Graphical User Interface:

- very easy to use
- workflow oriented architecture
- built-in plausibility control
- fast and seamless PUMA integration
- wide range of standard calculations
- extension packages for Diesel and Gasoline engines
- AVL Sensor Data Management SDM
Development package

- IndiModul Start (8 channels)
- IndiCom Advanced
  - Coldstart
  - Knock Analysis
  - Noise Analysis
- 1x Micro IFEM (Piezo or Multipurpose)
- 365C Crank Angle Encoder
- 2x uncooled Piezo-Tansducers with mounting tools
- Concerto with 5 NW licenses
- Care Support (2 years without SW subscription)
AVL INDICATING SYSTEMS
Advanced Line

IndiModul

IndiSet

IndiMaster
Detailed analysis of the indicating data (IFile) in the office

Investigation of the correlation between combustion values and testbed results

Sophisticated diagrams and graphical objects for clear result presentation

Advanced calculation library, easy to use with CalcGraf and Formula Editor

Automated data processing with scripting
Geometry of cylinder and ports (customer)

coeffs of discharge (customer)

Valve lift (customer)

\[ p_{\text{intake}}, T_{\text{intake}} \]

\[ p_{\text{cylinder}} \]

\[ p_{\text{exhaust}}, T_{\text{exhaust}} \]

Adjustment using pressure

Filter, Adjustment and Combustion Analysis

Adjustment using pressure
Together at the Test Bed

- short loop between simulation and measurement

- Application of Simulation Tools at the Test Rig

- Indication and Simulation Together
AVL VISIOSCOPE - OPTICAL ACCESS

- Camera-connection
- Cooling ducts
- Rod lenses with integrated fibres
- Rod lenses with cooling channel
- Objective lens
- Light entrance

Cooled endoscope

Rod lenses with cooling channel

Rod lenses

Rod lenses with integrated fibres

Uncooled endoscopes

Viewing direction

- Straight forward view
  - 0°
- Oblique view
  - 30°
- Oblique view
  - 70°
Example Visioscope Diesel Flame

-5.0 deg CA
DI_Diesel_flame
Example Visioscope Diesel Flame / Flame Temperature
Example Visioscope DI Gasoline
Example Visioscope Gasoline Wall Wetting
THANK YOU FOR YOUR ATTENTION