Analysis Led Design for Engine System Development to Meet US2010 Emission Standards

ERC - 2005 Symposium

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Analysis Led Design for Engine System Development

Worldwide Emissions Levels: 171 – 751 HP

Particulate [g/kW·hr]

NOx [g/kW·hr]

US02/04

US10

EURO-VI

Tier IV B

Tier IV A

EURO-V

Japan - NLT

EURO-IV

Transient

US07

Tier IV A

Transient

NOx [g/kW·hr]

Particulate [g/kW·hr]
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- Cycle Simulation Work
  - EGR system config.
  - VVT strategy
  - Air Handling strategy

- Cyber Modeling
  - Control strategy

- CFD Work
  - Combustion system optimization

- SCE Testing
  - Model validation

- MCE Testing
  - System validation
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Analysis Tool

Air System Simulation

CFD Combustion Code

Fuel System Simulation

Optimization

- Temperatures
- Pressures
- Air Flows
- NOx Conversion
- Inj Press
- Crank Position
- HRR
- Crank Position
- PM
- NOx
- Current
- Crank

Analysis Tool Diagram
Combustion CFD Tool Improvements

- Combustion model (extensive validation for multiple injection – up to 5 events)
- Improved kinetics mechanisms
  - Varying Cetane Number
  - More low temperature chemistry
- Complex Grids
- Grid independent spray modeling
- Computing Power

Can Refine The Grid to Reduce Grid Sensitivity Issues
Heavy Duty Engine Development

- EGR System
- Sensors
- Controls
- NOx Aftertreatment
- PM Aftertreatment
- VVT
- Combustion Recipe (Piston, nozzle, swirl)
- Fuel Injection Equipment
- Turbomachinery
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Fuel Injection Equipment Design Space

Nozzle Area (Cupflow)

Lube Oil Soot Limit and Power Density

Example #2

FIE Mechanical Limit

Example #1

Diffusion

Injection Pressure

2002 FIE

Lifted Flame

Injection Pressure

# of Holes

Orifice Diameter

Injection Pressure

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Example #1
Increasing injection pressure reduced the residence time in the particulate production zone.

Lower nozzle diameters and further increase in injection pressure result in lifted flames.

Increased mixing time occurs with lifted flames due to increased strain rate on the flame.
Soot Formation is a Function of Residence Time

Soot formation depends on equivalence ratio, temperature, and time.

- High Injection Pressure Reduces Residence Time
- Increasing Injection Pressure

**Equivalence Ratio**

**C₂H₂ Mass Fraction x 10⁻⁴**

15.0% O₂
1000 K
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Fuel Spray Images for Variation in Injection Pressure

Increasing Injection Pressure
Influence of Increased Injection Pressure on Spray Characteristics

**Liquid Penetration (mm)**

![Graph showing liquid penetration over time after SOE with increasing injection pressure]

**Gas Penetration (mm)**

![Graph showing gas penetration over time after SOE with CFD results]

**Increasing Injection Pressure**
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Emissions and Fuel Consumption for Varying Injection Pressure

**CFD Model**

**Engine Data**

![Graphs showing emissions and fuel consumption](image)

- **fsDPM (g/kg fuel)**
- **BSFC (g/kWh)**

- Increasing Injection Pressure
- $\Delta = 5$

**Symbols:**
- Circle - Smoke
- Diamond - bsfc

**Results:**

0.22 g/kW-hr bsNOx at 22 bar BMEP

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Brake Thermal Eff. (%) vs. fsNOx (g/kg)

Both diagrams show the relationship between Brake Thermal Efficiency and brake specific NOx emissions (fsNOx) for different BMEP (Brake Mean Effective Pressure) levels. The data points are color-coded for 5 bar, 7 bar, 10 bar, 15 bar, and 20 bar BMEP, illustrating how performance metrics vary with pressure.

All speeds and loads

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Conclusions for Example #1

- Higher injection pressure coupled with an optimized combustion recipe (bowl, nozzle, swirl) provide a cost effective option for US2010
  - Improved fuel economy
  - Continued reduction in engine out PM

- According to modeling results, lifted diffusion flames can be achieved for larger bore engines.
  - Difficult to extend to small bore engines

- Higher injection pressure requires significant FIE development.

- Analysis led design process utilized to provide optimized combustion recipe.

- Lower engine out PM provides lower cost of ownership by reducing PM aftertreatment cost and improving fuel consumption.
Example #2
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Fuel Injection Equipment Design Space

Nozzle Area (Cupflow)

- Lube Oil Soot Limit
- Power Density

- FIE Mechanical Limit

Example #1
- Diffusion
- Lifted Flame

Example #2

Injection Pressure

2002 FIE

Injection Pressure

# of Holes

Orifice Diameter

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Simulation of Transient Injector Performance of Dual Row Nozzle

Path Lines Colored by Static Pressure (psia)

FLUENT 6.3.13d, dp, segregated, skel

Jul 14, 2004

Path Lines Colored by Static Pressure (psia)

FLUENT 6.3.13d, dp, segregated, skel

Jul 15, 2004
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Spray Images for Increased Cupflow Nozzle

100% Load

Spray Rig

CFD Model

25% Load

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Improving Smoke and Combustion Stability with Nozzle Design and FIE Calibration

bsNOx < 0.16 g/bhp-hr at 20 bar BMEP

Nominal Diameter

9% Smaller Diameter

bsNOx, Bosch #, SOI (ATDC)

Nominal Diameter – Engine Data
Nominal Diameter – CFD Model
Lower Diameter – Engine Data
Lower Diameter – CFD Model
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1998 Engine

Gross Indicated Thermal Eff. (%) vs. Ignition Delay (msec)


g/kg fsNOx ~ 0.2 g/hp-hr BSNOx

1 g/kg fsNOx ~ 0.2 g/hp-hr BSNOx

Bosch Smoke Number

5.0 bar
10 bar
15 bar
20 bar

Gross Indicated Thermal Eff. (%) vs. fsNOx (g/kg)
Conclusions for Example #2

- Higher cupflow and injection pressure provide an option for US2010.

- Detailed CFD modeling of the injector internal flow required to achieve desirable flow characteristics.

- Analysis led design process utilized to provide optimized combustion recipe.

- Lower engine out PM provides lower cost of ownership by reducing PM aftertreatment cost and improving fuel consumption.
Light Duty Engine Example
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Extending the LTC Zone

- Improved Air Handling
- More Capable Fuel System
- Combustion Recipe
- FIE Calibration
- Compression Temperature
- Increased Injection Pressure

Engine Speed [ rpm ]

Torque [ ft-lb ]

Engine Speed

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Combustion System Design And FIE Calibration

Engine Emissions Results
EGR Sweep at 1800 rpm and 8 bar BMEP

- Bowl #1 - Engine Data
- Bowl #2 - Engine Data
- Bowl #3 - Engine Data

CFD Predictions
EGR Sweep at 1800 rpm and 8 bar BMEP

- Bowl #1 - Computed
- Bowl #2 - Computed
- Bowl #3 - Computed

CFD Model Captures Trends
Config. #2 CFD Results

1800 RPM at 8 bar BMEP

0.0 500 1000 1500 2000 2500 3000

Gas Temperature (K)

0 500 1000 1500 2000 2500 3000

Equivalence Ratio

Ideal Mixing Line

Ignition Zone

Config. #2 does not provide enough mixing to eliminate fuel rich zones.

Fuel rich zones lead to more soot formation and higher NOx.

Soot*

Soot**

NOx

1° atdc 4° atdc 10° atdc 30° atdc

*SAE 2001-01-0655

**SAE 880423

Computed Equivalence Ratio Evolution

Config. #2 does not provide enough mixing to eliminate fuel rich zones.

Fuel rich zones lead to more soot formation and higher NOx.
Impact of Increased Injection Pressure

1800 RPM at 8 bar BMEP

Noise (dBA) vs. Smoke (FSN)

Increased Injection Pressure

2002 FIE

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Equivalence Ratio ($\phi$) vs. Temperature (K)

- Mixing line
- Ignition
- $5\%$ $O_2$
- $21\%$ $O_2$
- $15\%$ $O_2$
- $8\%$ $O_2$
- $5\%$ $O_2$

$NO_x$
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NOx Distribution

2002 Engine Results

New Engine Results

Engine Speed (rpm)

BMEP (bar)

NOx < 0.2 g/mi
Conclusion for LD Example

- Higher injection pressure important for light duty application
  - Achieve noise and smoke requirements at higher loads within emissions certification region
  - Important in mode transition
  - Important for power density growth

- Multiple injection characteristics extremely important.

- Optimizing a combustion recipe for a wide range of injection pressure needed
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Conclusions

• The Analysis Led Design Process is vital to match the right technology to meet emissions standards and customer requirements.

• Analysis tools vital for down selection of technology.

• Calibrated modes are part of the deliverables to the engine platform teams.

• All engine development programs at Cummins uses the Analysis Led Design Process.