EGR Distribution in Engine Cylinders Using Advanced Virtual Simulation

Xuetong Fan, Brian Bolton and Nabil Hakim

Exhaust Gas Recirculation (EGR) is a well-known technology for reduction of NOx in diesel engines. With the demand for extremely low engine out NOx emissions, it is important to have a consistently balanced EGR flow to individual engine cylinders. Otherwise, the variation in the cylinders’ NOx contribution to the overall engine emissions will produce unacceptable variability.

This presentation will demonstrate the effective use of advanced virtual simulation in the development of a balanced EGR distribution in engine cylinders. An initial design is analyzed reflecting the variance in the EGR distribution, quantitatively and visually. Iterative virtual lab tests result in an optimized system.
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Agenda

• Background
  – EPA Emission Regulations
  – EGR Technology

• EGR Distribution Simulation Methodology
  – Integration of 3-D Computational Fluid Dynamics (CFD) and 1-D Cycle Simulation

• Case Study

• Summary
EPA Emission Regulations

2004: EGR is a Promising Technology
2007: Likely Requires EGR + Aftertreatment
EGR Technology
NOx Reduction with PM Penalty (FTP)

EGR System “A” (SAE 2000-01-1933)

EGR System Refinement Improves Trade-Off

EGR System “B”

No EGR Baseline

PM Emission, g/bhp-hr

NOx Emission, g/bhp-hr
EGR System Engineering

- Air System and Turbocharger Matching
- Fuel Injection Technology
- Combustion System Optimization
- Smart Controls
- Design Engineering
EGR Distribution

• Requirements
  – Even or Minimal Cylinder-to-Cylinder EGR Variation
  – Efficient EGR and Air Mixing in Intake Manifold
  – Minimal Pressure Loss in EGR Delivery System

• Challenges
  – EGR & Air Mixing and Pressure Loss Trade-Off
  – EGR Distribution is Extremely Difficult to Measure
EGR Distribution Technology

• Advanced Virtual Lab Simulations
  – 1-D Cycle Simulation of Complete Engine System
  – 3-D CFD Analysis of Intake Manifold with EGR Mixing
  – Tool Integration: Coupled CFD and Cycle Simulation

• Application of Advanced Virtual Lab Tools in Design Engineering
Virtual Lab Tool: Cycle Simulation

- Entire Engine System
- EGR and Charge Air Flow
  - Consider Engine Dynamics
  - Assume Instantaneous and Perfect Mixing of EGR & Air

- Cycle Simulation Alone:
  - Can not Account for Air/EGR Mixing Rate
  - Predicts Near-Even EGR Distribution to all Cylinders
Virtual Lab Tool: 3-D CFD

- CFD Model for Intake Manifold with EGR Inlet or Mixer

- CFD Capabilities
  - 3-D Fluid Dynamics
  - Turbulent, Compressible Flow
  - Transient Simulation
  - Multi-Species Tracking
  - Calculate EGR & Air Mixing
  - Flow Field Visualization

- CFD Boundary Conditions:
  - Interaction with Cycle Simulation
Coupled Simulation:
3-D Intake Manifold CFD Mesh Embedded Within a 1-D Cycle Simulation Complete Engine Model

- 3-D and 1-D Simulations Run Simultaneously (“Coupled Analysis”)
- Boundary Conditions Exchanged On-the-Fly across 1-D/3-D Interfaces
- Calculate EGR Mixing and Distribution
Case Study

- Simple design chosen for this case study
- CFD Model Contains 150,000 Cells
Visualization of Coupled CFD Solution

Flow Field:
Velocity Vectors

Color Scale:
EGR Mass Fraction

Firing Order:
1-5-3-6-2-4
Cylinder 6 Snap Shot

 crank Angle: 60.

 Z (mm) = 485.

 PROSTAR 3.10

 SC 5-EGR

 TIME = 0.821058
 LOCAL MX = 0.1823
 LOCAL MN = 0.1103E-01

 (60° CA)

 CR Intake Manifold
Cylinder 1 Snapshot

Crank Angle: 415

Z (mm) = 485

(415° CA)

S60 CR Intake Manifold
Cylinder 1 Snapshot

Crank Angle: 465°

Z (mm) = 485

PROSTAR 3.10

SC 5-EGR

\[ \text{TME} = 0.866055 \]
\[ \text{LOCAL MX}= 0.2574 \]
\[ \text{LOCAL MN}= 0.5701E-01 \]

(465° CA)

S60 CR Intake Manifold
Cylinder 1 Snapshot

Crank Angle: 490°

Z (mm) = 485

(490° CA)

PROSTAR 3.10

SC 5-EGR

TIME = 0.868332
LOCAL MX = 0.2025
LOCAL MN = 0.2490E-01

Values:
0.2000
0.1900
0.1800
0.1700
0.1600
0.1500
0.1400
0.1300
0.1200
0.1100
0.1000
0.9000E-01
0.8000E-01
0.7000E-01
0.6000E-01
0.5000E-01
0.4000E-01

560 CR Intake Manifold
Predicted EGR Distribution

- Cycle Simulation Alone Predicts Near-Even EGR Distribution
- Coupled Analysis Captures Cylinder-to-Cylinder Variation
Coupled CFD Solution: EGR Mass Fraction in Inlet Region

Coupled Analysis Simulates Air/EGR Mixing Process
Coupled CFD Solution: EGR Concentration in Manifold

Diagnosis:
Insufficient Mixing Leaves “Rich” and “Lean” Regions in Intake Manifold

Firing Order:
1-5-3-6-2-4
Summary

- Advanced Virtual Lab Tools — Integral Part of EGR Technology

- Coupled CFD & Cycle Simulation Predicts EGR Distribution that is Difficult to Measure with Today’s Test Methods

- Advanced Simulations Evaluate Virtual Hardware in Design Stage and Identify Root Causes