Investigating Engine Systems with CFD Tools

Yong Yi
Fluent Inc.
Outline

- Motivations
- Applications and Challenges for CFD Tools
- Integration of CFD Tools with Product Design Cycle
Motivations

- Engine and Automobile Manufacturers are facing ever increasing challenges of meeting:
  - Legislative Regulations
    - Emission and fuel consumption requirements
  - Power output requirements
  - Durability and Reliability requirements
    - e.g., Thermal Management
  - Profitability Targets and remaining Competitive
    - Cutting down prototype design costs
    - Shorten design cycles

- CFD (computational fluid dynamics) can play a role:
  - Less expensive
  - Early investigation tool
  - Troubleshooting tool during testing and manufacturing

- The challenges:
  - Robustness, efficiency and accuracy of the CFD tools
  - Integrating CFD tools with product design cycle
Applications and Challenges of CFD Tools

**Matured applications**: Steady-state, single-phase, non-reacting flow and heat transfer

- Robustness
- Accuracy
- Efficiency
- Usability
- How does it fit in the design cycle?

**Advanced applications**: Transient, combustion and chemical reaction, multi-phase flow
Example 1: Induction System

- Fixed-Valve-Lift Steady-State Flow Simulations
  - Simple and inexpensive analysis
  - Predict mass flow rate / pressure drop at various lifts
  - Correlating with the engine performance
  - Visualize airflow within the inlet port and chamber
  - Predict flow distribution around valve
  - High accuracy: within 5%

- Challenges:
  - Effects of moving components is not included

- Solutions:
  - Transient simulations with moving components
Example 2: Engine Intake Flow

- Transient Flow Simulations with Moving Components
  - Predicting flow structure with real engine operating conditions
  - Visualizing the flow and mixing process in the combustion chamber
  - Correlating with the engine performance
  - Robust process

- Major concerns are mesh quality and turbulence models
  - Benchmark may be required
Example 3: Intake and Exhaust Manifolds

- Steady-state and Transient flow simulations
  - A matured application with good accuracy
  - Improving manifold can significantly improve the engine performance
  - CFD simulation can identify where to improve the shape of the manifold

- Question:
  - How to get reasonable boundary conditions at inlets or outlets of the manifolds?

- Answer:
  - Coupling CFD tools with system simulation tools

Prediction of distribution of secondary gas (EGR and PC)
Example 4: Fuel Injection System

- Study the internal flow in fuel system including fuel injector
  - Steady-state with fixed needle position
  - Transient with described needle motion profile
  - Cavitation and other multiphase phenomena can be studied

- Challenges:
  - Needle motion profile is determined by flow condition

- Solution:
  - Flow force + dynamic mesh models
  - Fluid-Structure Interaction simulations (FSI) with FEA tools
  - Flow has to be resolved extremely accurate
Example 4: Fuel Injection System

Simulating the cavitating flow in a diesel injector with moving needle

Pressure

Vapor Volume Fractict
Example 5: Engine Combustion System

- Transient flow and combustion simulations
  - Investigating fuel injection and mixing
  - Investigating flame interaction with flow and turbulence
  - Predicting pressure, heat release, and pollutants concentrations

- Challenges
  - Further model and methodology developments are necessary
  - Spray and combustion models usually need careful calibration
  - Emission prediction is still a challenge
  - Cycle-cycle variation has become a topic for certain applications
Example 6: Engine Cooling Systems

- Water-jacket flow and heat transfer
  - Usually steady-state simulation
  - Very matured for single-phase flow
  - Pump simulation can be included
  - Boiling can be included
  - Established procedures to transfer flow and thermal data to FEA codes

- Challenges:
  - Boundary conditions are changing during engine cycles

- Solutions:
  - Coupling with cooling system simulation tools
Example 6: Engine Cooling Systems

- Piston cooling
  - Transient simulation with moving parts
  - Predicting heat transfer coefficients and temperature distribution for the piston
  - Established procedures to transfer flow and thermal data to FEA codes

- Challenges:
  - The thermal boundary condition on the combustion chamber-side of the piston is not readily to obtain
Example 7: Exhaust Aftertreatment Systems

- Industry concerns
- CFD (Fluent) models

**Performance**
- Flow/heat loss
- Conversion efficiency
- Trapping efficiency
- Light-off duration

**Durability**
- Thermal stress

**Flow and heat transfer models**
**Reaction models**
**Spray models**
**Fluid-Solid Interaction models**
**DPF models**
Example 7: Exhaust Aftertreatment Systems

◆ Flow analysis
  ▪ Simple simulation
  ▪ Provide indications to address the performance of the device
    - Flow distribution
    - Uniformity
    - Heat loss
    - Pressure drop

◆ Fluid-Solid interactions
  ▪ Resolve heat transfer and reactions in fluid and solid regions
  ▪ Critical for unsteady simulation, especially during the engine cold-start period
  ▪ Required for durability study of the substrate

◆ Reacting flow analysis
  ▪ Predict reactions based on local flow and thermal conditions
  ▪ Predict pollutants conversion efficiency

◆ Filtration modeling
  ▪ Predict the soot loading and corresponding pressure drop for a filter
  ▪ Provide initial conditions for soot regeneration modeling
Example 7: Exhaust Aftertreatment Systems

General modeling approach

- **Single-channel model**
  - Use only one channel to represent the flow and reactions of the device
  - Precisely resolve the flow and reaction in each single channel
  - Cannot accurately predict the performance when the flow is not uniform at the inlet of the converter

- **Macroscopic model**
  - Approximate the flow and reaction using the porous media model
  - Flow in each channel is not fully resolved
  - A simple approach that can handle non-uniform flow easily
  - It becomes an inaccurate representation for DPF

- **Representative Channels model**
  - Use some representative channels to resolve the flow and reaction
  - Provide a practical tool that balances accuracy and efficiency
  - The choice of representative channels could be tricky when flow is very un-uniform at the entrance of the device.
Example 7: Exhaust Aftertreatment Systems

A transient simulation for a power-plant natural gas engine aftertreatment device during cold-start

Forward Flow

Reverse Flow

Temperature distribution

Mass fraction of CH4 and CO at outlet
Example 7: Exhaust Aftertreatment Systems

Soot deposition history in the filter

A single-channel model for I
Example 7: Exhaust Aftertreatment Systems

Temperature distribution during soot regeneration
Example 7: Exhaust Aftertreatment Systems

Temperature distribution at centerline
Summary of Current Applications

- CFD has been used extensively and successfully in single phase non-reacting applications.
- CFD has been attempted for engine combustion and reacting flows. Further improvement is desired:
  - Robustness
  - Simulation time vs. accuracy
  - Resolving sophisticated physics
  - Usability
- CFD has not been completely integrated into the design cycle:
  - Cumbersome communication with other CAE tools
  - Designers have no access to CFD tools
Integrating CFD tools with product design cycle

Where does CFD fit?
Integrating CFD tools with product design cycle

Process gap often exists between different groups:
- Designer – CFD Analyst
- CFD – FEA
- CFD – System Analysis
- CFD – Optimization Tool
- CFD Analyst – Designer

Designer waits until his design is finished and then “throws it over the wall” to analysis which in turn makes suggestions and throws it back for rework. This serial process wastes time and can create a competitive atmosphere, rather than fostering an environment of shared goals.

A total solution integrates all tools together...
Product Engineering / Design Process

- The concept of Virtual Product Development (VPD) or Digital Prototyping (DP)
  - Environment where all phases of the product design process use an integrated combination of both simulation software & traditional techniques

- Through VPD, cost effective designs with higher levels of reliability can be achieved in less time than using only traditional physical processes

- The CAE – of which CFD is a part – is an essential part of VPD / DP
FSI: CFD + FEA

- One-way data mapping can be used to transfer CFD data to FEA for structural analysis
  - Well-established
- CFD can be dynamically linked with FEA for the following purposes
  - Transferring thermal and flow data between CFD and FEA codes
  - Providing more realistic conditions for flow and structural analyses
    - Moving the objects due to flow force
    - Simulating deformation of the boundaries due to local flow / thermal conditions
  - The coupling often done with a coupling interface, e.g., MPCCI
- Applications in engine system
  - Fuel injection system
  - Manifolds
  - Aftertreatment devices
Examples of FSI:

Under high pressure

Flow control value cross-section

Under low pressure

Flow control valve

Deforming flap
Example of FSI: Heat Transfer in Cylinder Head

Temperature distribution

Uncoupled Simulation

Coupled Simulation
CFD + 1D System Simulation Tools

- CFD can be linked with 1D system simulation tools
  - 1D codes provide boundary conditions to 3D CFD model
  - 3D CFD model feeds back the predicted flow / temperatures
  - Well-established coupling
  - CFD + Engine system tools
  - CFD + Cooling system tools
1D-3D Coupling: Engine System

CFD component

EGR concentration

 Courtesy of Cummins Engine Company
1D-3D Coupling: Cooling System

Courtesy of DaimlerCrysler

Pressure distribution
CFD + Optimization Tool

- CFD can be linked with optimization tools to automate the parametric study of designs
  - Optimize the operating parameters, e.g., injection timing, EGR, etc.
  - Optimize the geometry, e.g., port design, piston shape, etc.
- Usually CFD, CAD and mesher are driven by the optimization codes
  - For change of geometry, “mesh morpher” is used.
CFD – Optimization Examples

**INPUT**
- Vane Number
- Short-Long Ratio
- Front Radius
- Taper Length

**Direct Interface**

**iSIGHT**
- Objective: Maximize HTR
- Sensitivity Study
- Strategy: DOE & Monte Carlo

**OUTPUT**
- HTR (Heat Transfer Rate)
- AFR (Airflow Rate)
CFD – Optimization Examples

CFD and optimization tools linked with mesh morphor

- Animation shows how the original CFD model is morphed to fit a new geometry
- Large shape changes are demonstrated
- Element quality retained to acceptable levels even after large shape change

Graph showing up to 90% reduction of engineering time.
Engine Intake Port Shape Optimization

Flow maximized using Parametric CFD model & Process Automation

DOE Matrix
CFD - Designer

- CFD tool has, traditionally, been used only by analysts
- CFD can be used in early concept design stage by designers
  - **Shifting of roles**

- Usually two approaches:
  - Template-based tool
    - CFD tool customized for specific application or client
    - Flexible and tailored to the specific application
  - Wizard-driven tool
    - Automated and design-oriented CFD tool
    - Usually general purpose
CFD – Designer: An Example of Template-driven Tool

Steady-state engine port flow analysis

User Inputs
- No. of Lifts
- Lifts Values
- Inlet/Outlet BC

Interface

Journal for geometry cleanup & surface mesh

Plugin for design

HTML Report

Volume mesh

CFD Simulation
CFD – Designer: An Example of Template-driven Tool

Steady-state engine port flow analysis
CFD – Designer: An Example of Wizard-driven Tool