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ICSC2014

IDAJ CAE Solution Conference

CONVERGE在国外发动机仿真中的应用

艾迪捷信息科技（上海）有限公司
IDAJ 技术部 张志宏

主要内容

- 流动特性
- 喷雾研究
- 燃烧系统

主要内容

- 流动特性
- 喷雾研究
- 燃烧系统

流动特性

关键词： 涡流、柴油机、优化

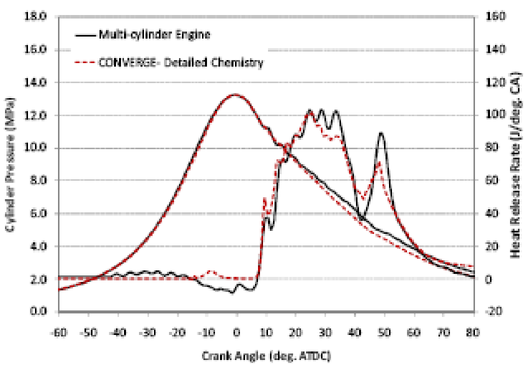
流动特性

- 涡流比对柴油机燃烧系统的影响
  - 涡流运动强化燃气混合、降低排放
  - 进气道上游节流阀片调整各工况点涡流比
- 对最新的燃烧系统分析涡流对燃烧、性能及排放的影响
  - 全负荷及部分负荷性能

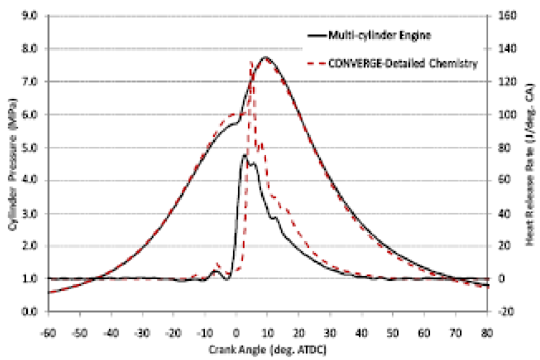
流动特性

CFD模型验证

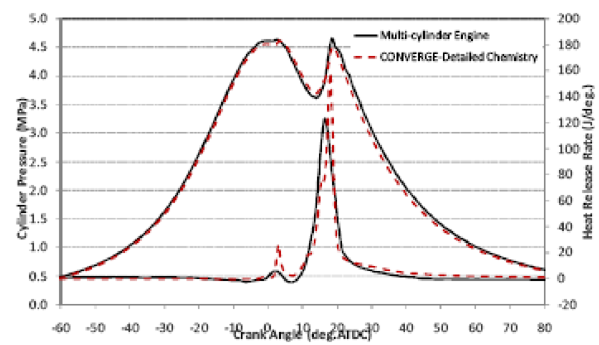
High Load Point (2800 RPM/14 Bar)

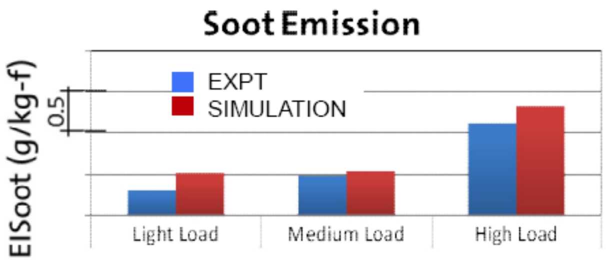


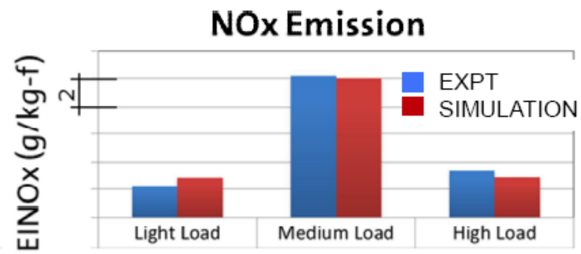
Medium Load Point (1800 RPM/6 Bar)



Light Load Point (1400 RPM/4 Bar)







"Good quantitative agreement with the experimental measurements!
Well predicted cylinder pressure,heat release,soot and Nox across different speed/load points"

流动特性

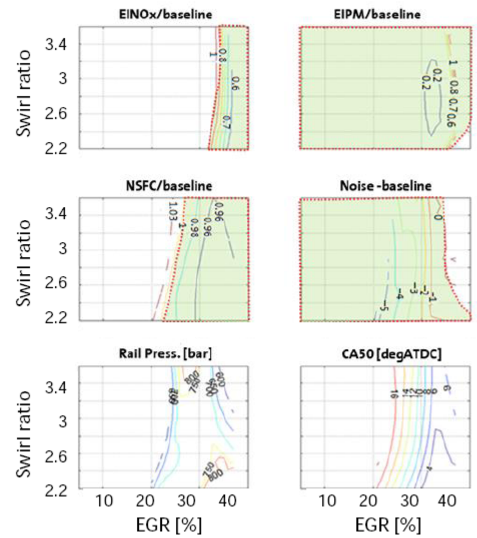
全载荷及部分载荷仿真优化结果

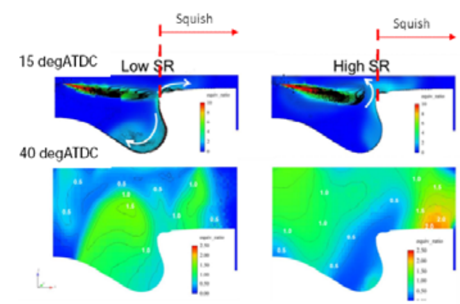
Conclusions (full-load)

- Increasing swirl caused:
  - Longer combustion duration and lower NMEP at same exhaust temperature (limiting factor for all conditions).
  - Higher smoke emissions, but within the 3FSN limit
  - Lower sensitivity of NMEP with respect to boost, indicating a deterioration in air utilization.
- 3D-CFD spray combustion related to the spray penetra
  - The high swirl motion prevents t bowl and squish regions.
  - Combustion takes place mostly i explaining the longer duration ar
  - High local equivalence ratio (>2)

Conclusions (part-load)

- 6 keypoints relevant for NEDC and WLTC were tested. Design of Experiments technique evaluated the effects of swirl ratio, EGR rate, rail pressure and injection timing.
  - For relatively high loads, high swirl ratio increased both fuel consumption and emissions, due to spray penetration issues.
  - For low loads, the optimal SR depended on combustion noise constraints, due to the interaction between rail pressure, spray penetration and swirl.
- Cycle-based fuel consumption and engine-out NOx/PM were estimated for a small vehicle application for variable- and fixed-swirl solutions.
  - A fixed 2.5 swirl ratio geometry introduced a penalty of around 1% in fuel consumption with respect to a variable-swirl solution, with similar engine-out NOx and PM emissions.
  - In terms of rated power capability, the fixed 2.5 swirl ratio configuration represented a deterioration of around 1.8-bar NMEP.
  - Consequently, a fixed swirl ratio configuration may be only applicable to mid-to-low power density applications.





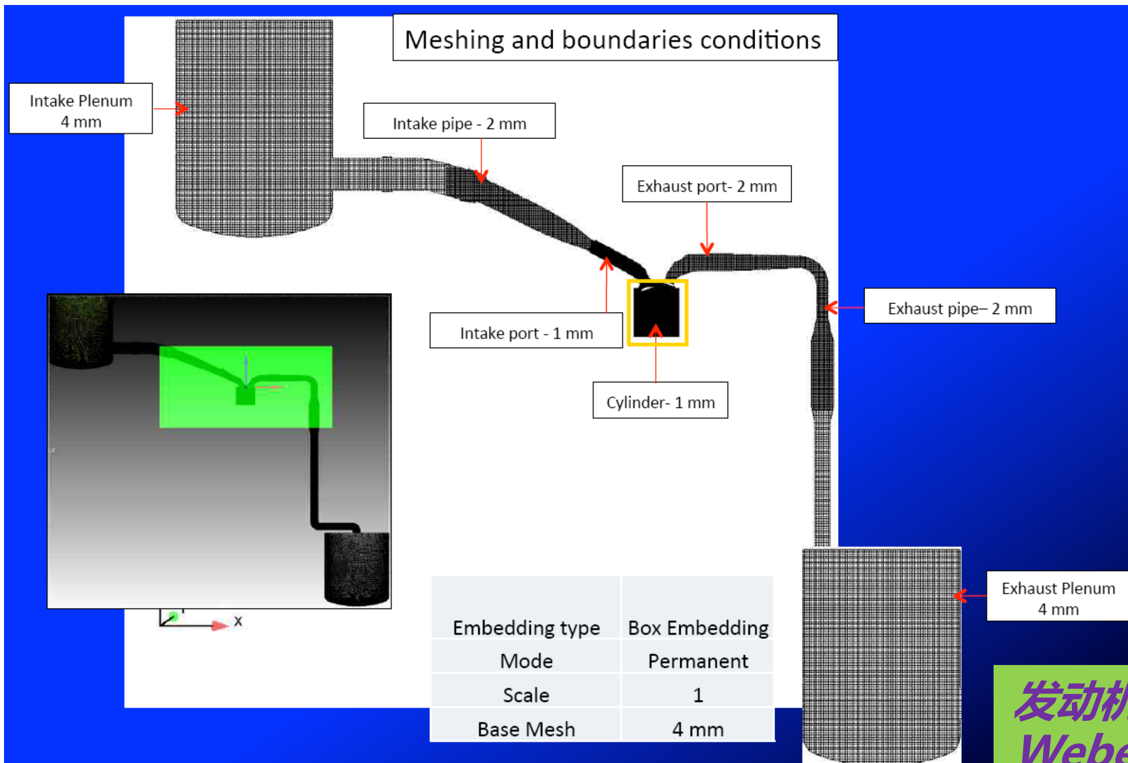
Spray penetration and equivalence ratio distribution for low and high swirl-ratio at rated-power.

流动特性

关键词： 滚流、增压DI

流动特性

- 增压GDI发动机滚流运动应用



Embedding type	Box Embedding
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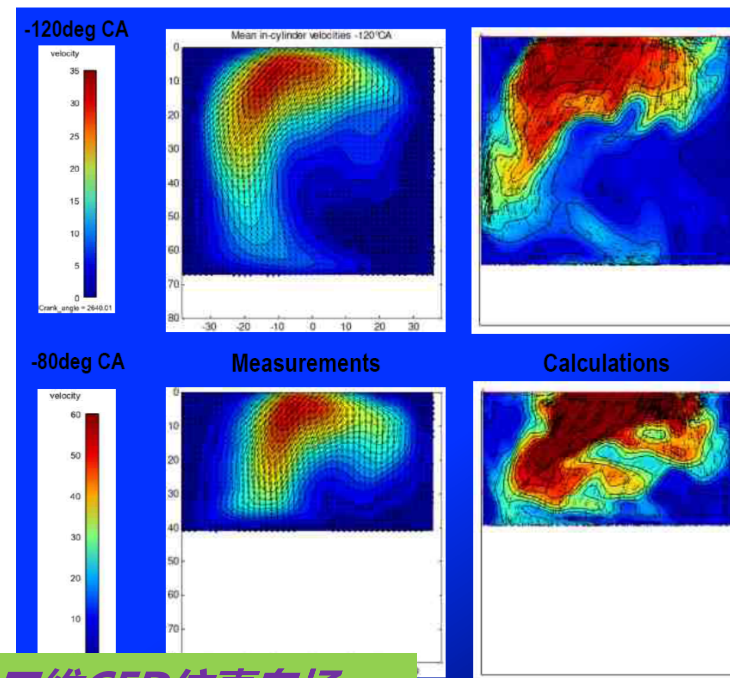


发动机三维CFD仿真专场 Webex报告

主要内容

- 流动特性
- 喷雾研究
- 燃烧系统

喷雾研究

Argonne NATIONAL LABORATORY

关键词：

喷孔流动、喷雾模拟、子模型开发

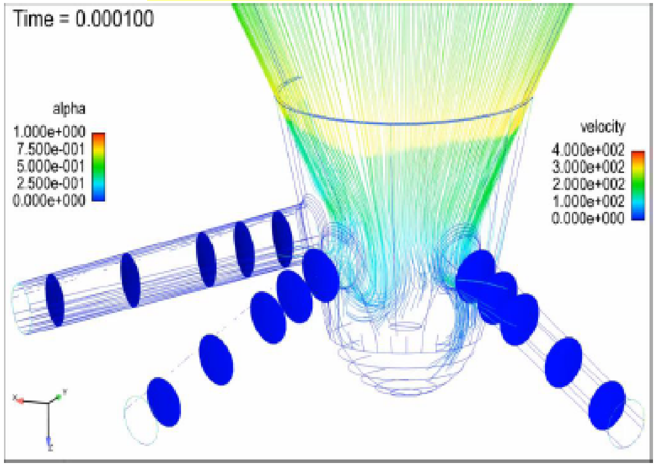
喷雾研究

- 喷嘴模拟中的多相流问题
  - 高密度比流动
  - 精细界面（已解决）
  - 气泡流动/分散粒子（亚格子模拟）
  - 相变（气蚀，闪蒸，蒸发等）
- 目标
  - 发展高精度的物理模型无需校核参数即可与实验匹配

↓

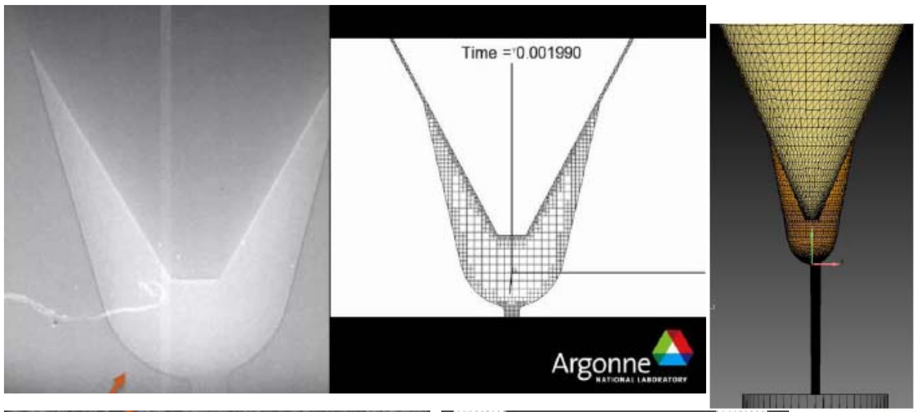
HPC

SAE paper 2014-01-1426



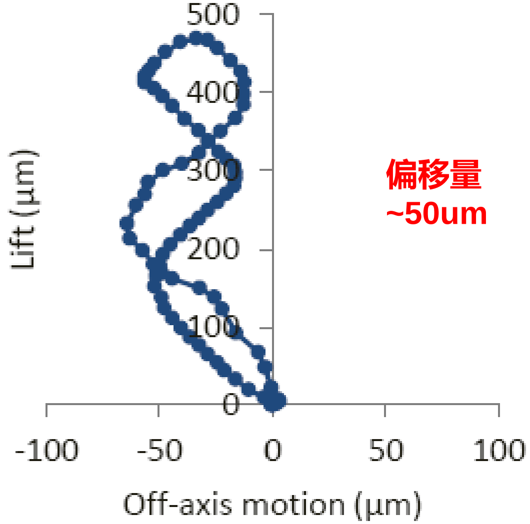
喷雾研究

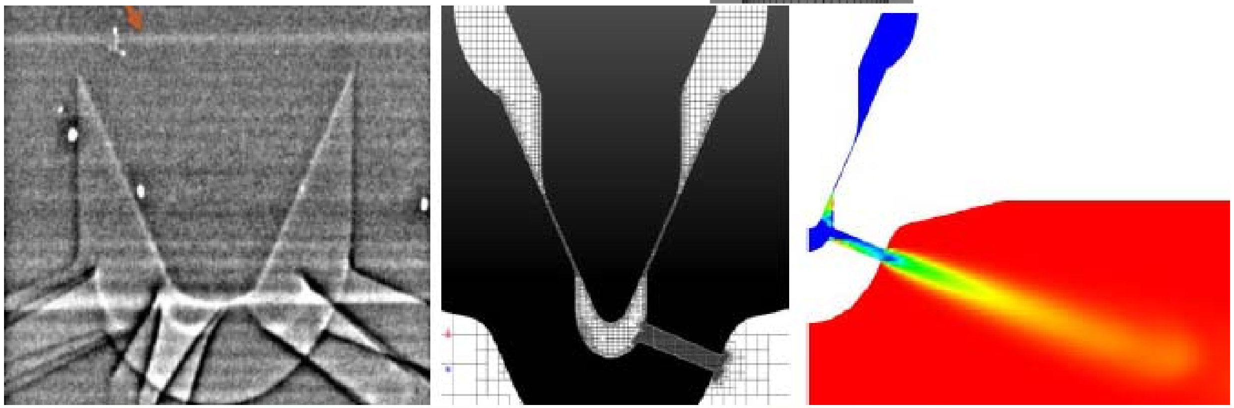
- 基于X射线数据定义针阀的偏轴运动
- 可以预测针阀结构对喷雾的影响



1-hole injector, Spray A *(ECN)*

Lift vs. off-axis motion





9-hole injector, Cummins XPI *(CRADA project)*

喷雾研究

Argonne NATIONAL LABORATORY

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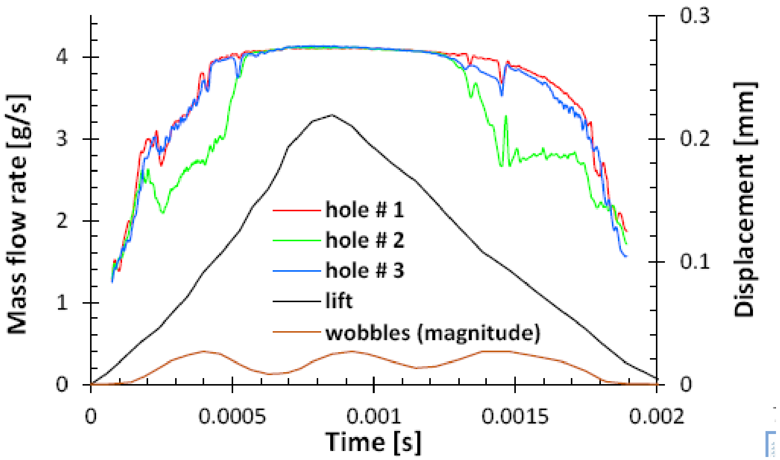
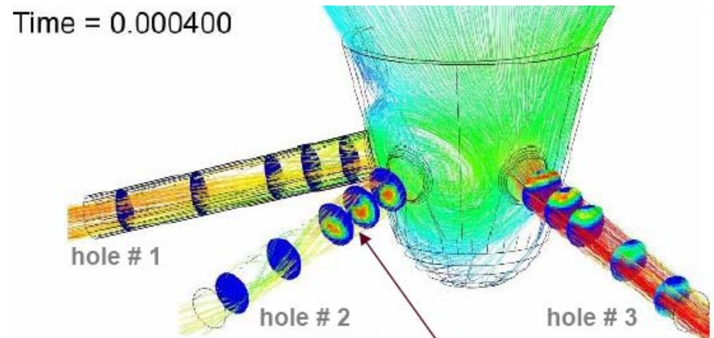


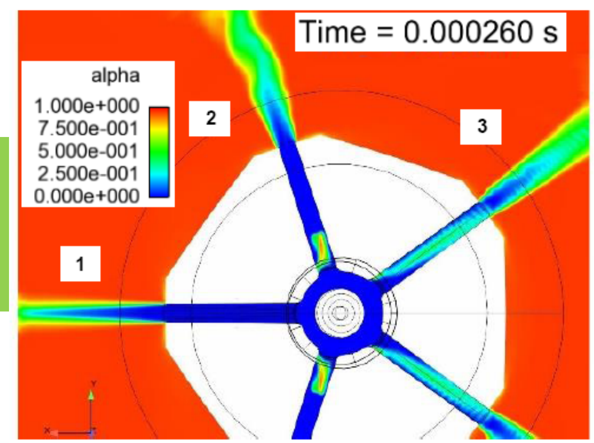
针阀偏移引起孔间流量变动



“串状”气蚀

考虑针阀偏振效应的同类研究中使用CONVERGE工具研究的结果最出色

孔2的旋流射流现象
孔3的半阻塞流动现象



喷雾研究

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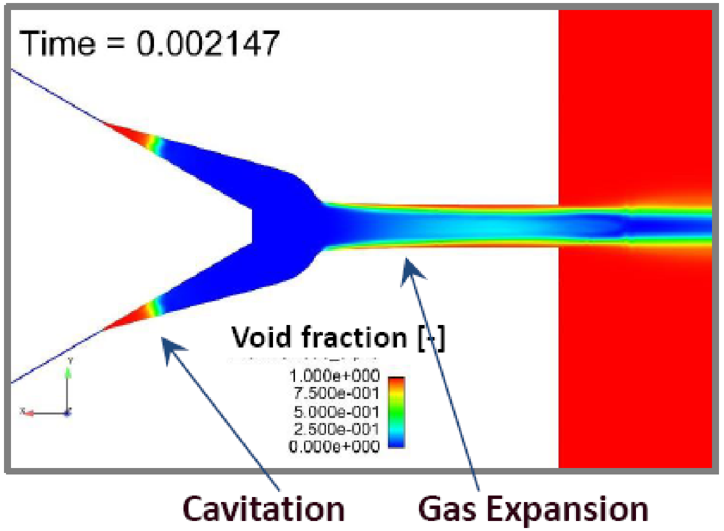
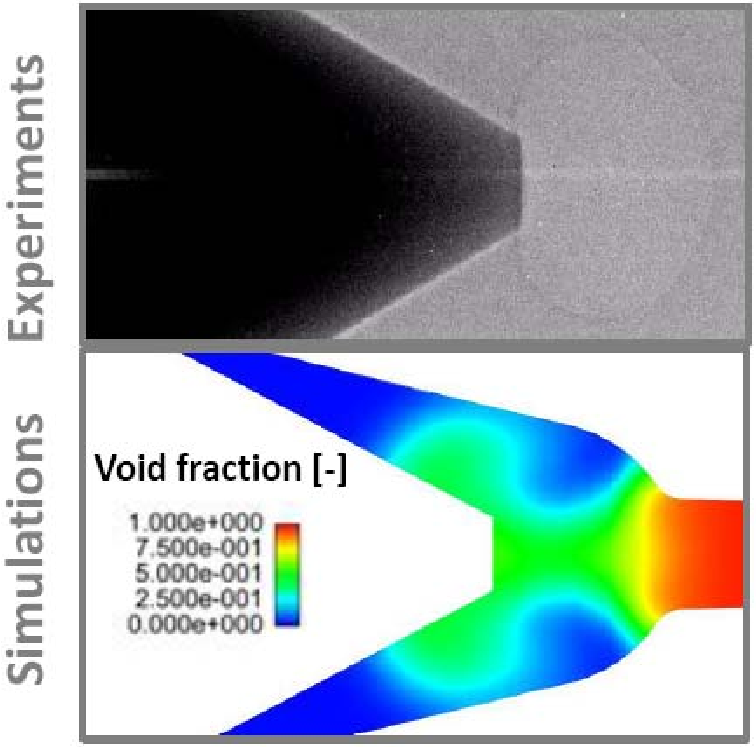


最小网格尺寸5um，2千多万网格数量
最小时间步长1e-9s



高精度仿真，同类模拟中最出色
揭示了压力室（针阀和喷孔之间的空间）内空气倒吸现象背后的物理原因

喷雾研究

- 基于X射线数据定义针阀的偏轴运动
- 可以预测针阀结构对喷雾的影响

- **Nozzle flow Simulations**
  - 10-15 μm resolution is sufficient to capture bulk flow features
  - 5 μm or finer may be necessary to capture the transients during the needle opening and closing
  - Needle wobble has a profound influence on plume-to-plume variations

喷雾研究

- LES湍流模型

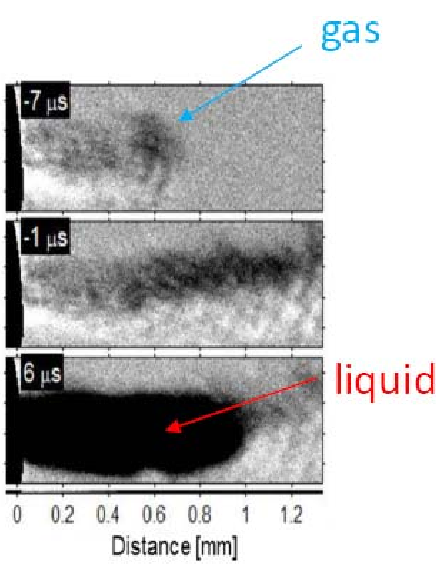
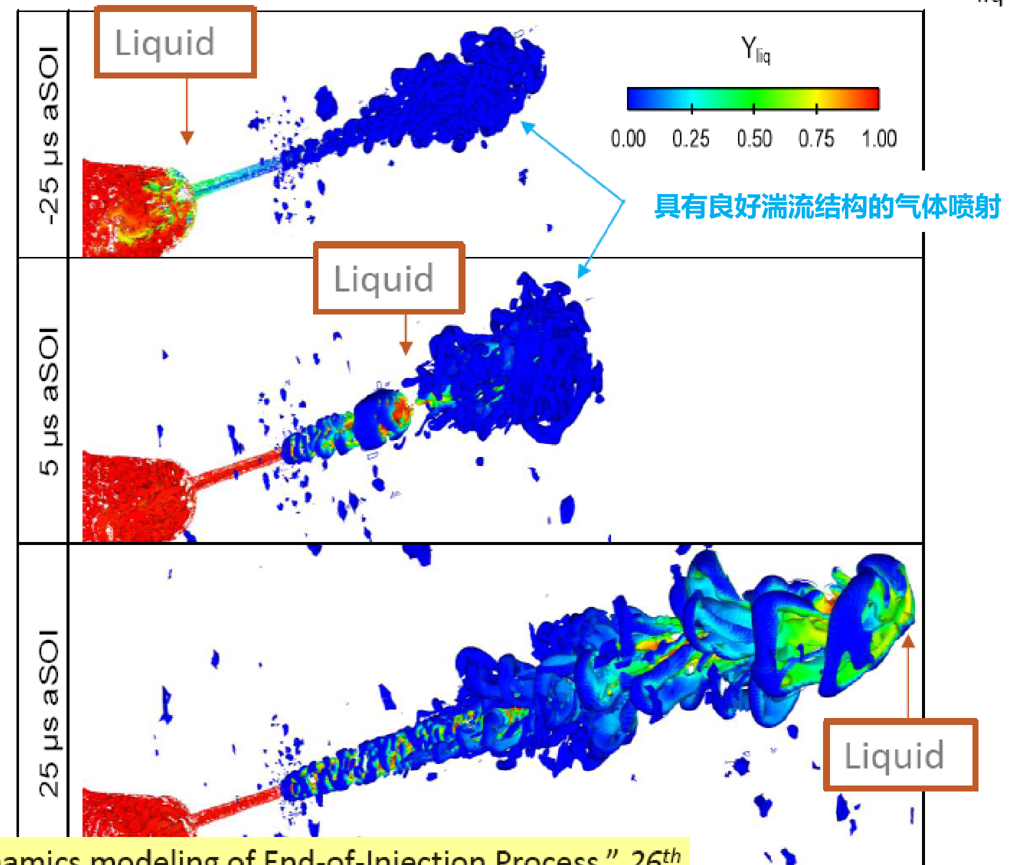


Figure 14. Long-distance microscopy high-speed imaging during the start of injection with diffused back lighting.

L. Pickett et al. SAE 2013

在液体喷射之前事实上有若干微秒的气体或蒸汽喷射

Vortexes (Q-criterion) colored by liquid mass fraction (Y_{liq})



M. Battistoni, A.L. Kastengren, C.F. Powell, S. Som, "Fluid Dynamics modeling of End-of-Injection Process," *26th ILASS Americas*, Portland, OR, May 2014

喷雾研究

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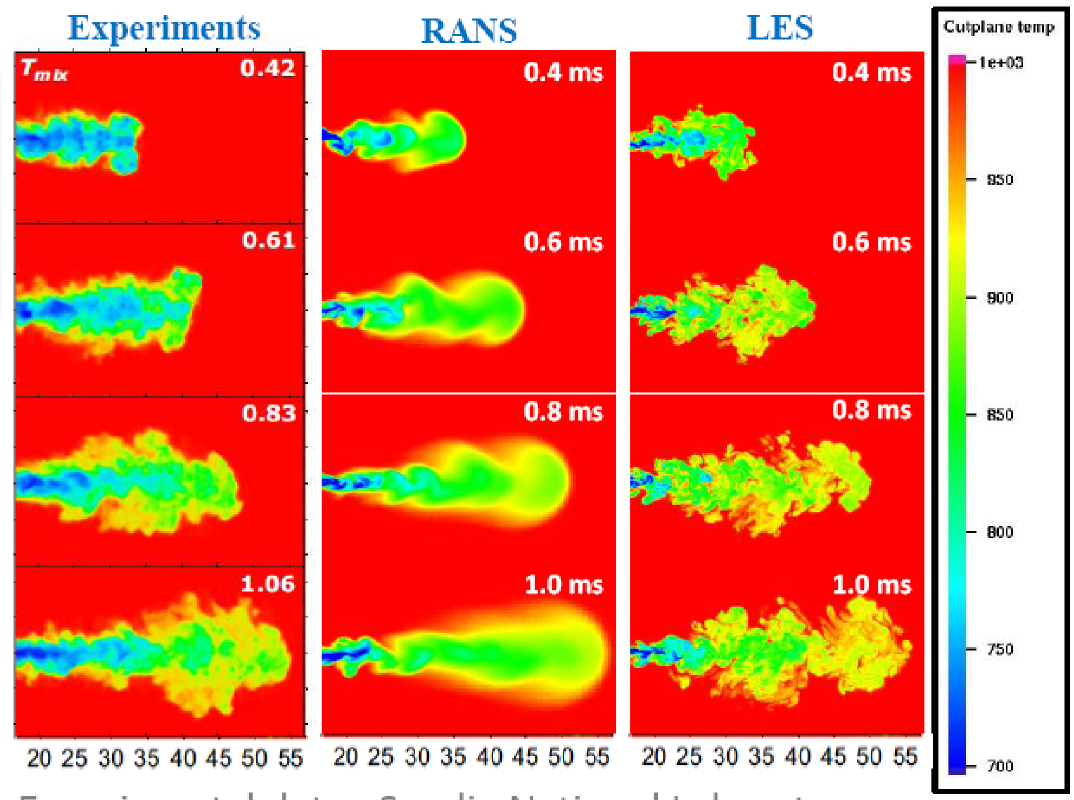
■ LES湍流模型



Experimental data : Sandia National Laboratory

项目影响：
1. **LES模型可以捕捉RANS方法无法预测的流动结构**
2. **LES可以捕捉循环变动**

喷雾研究

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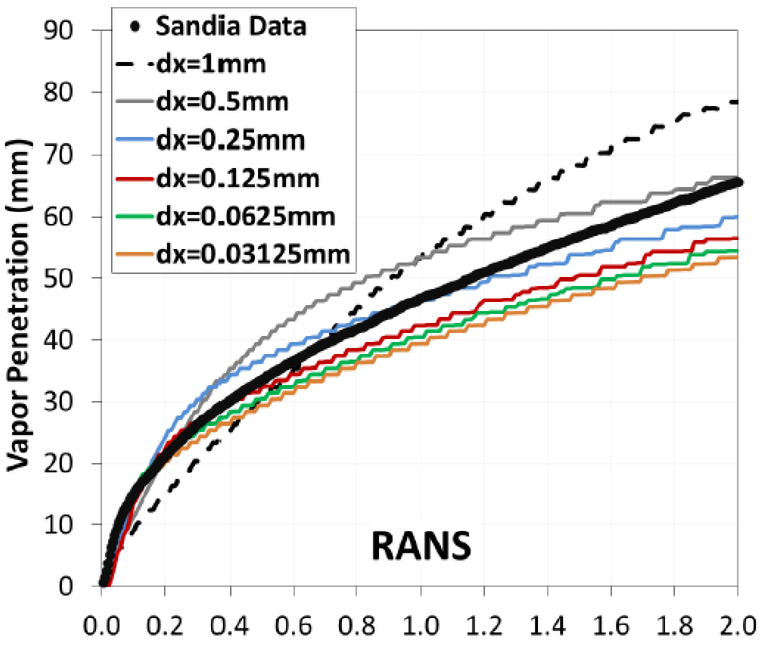
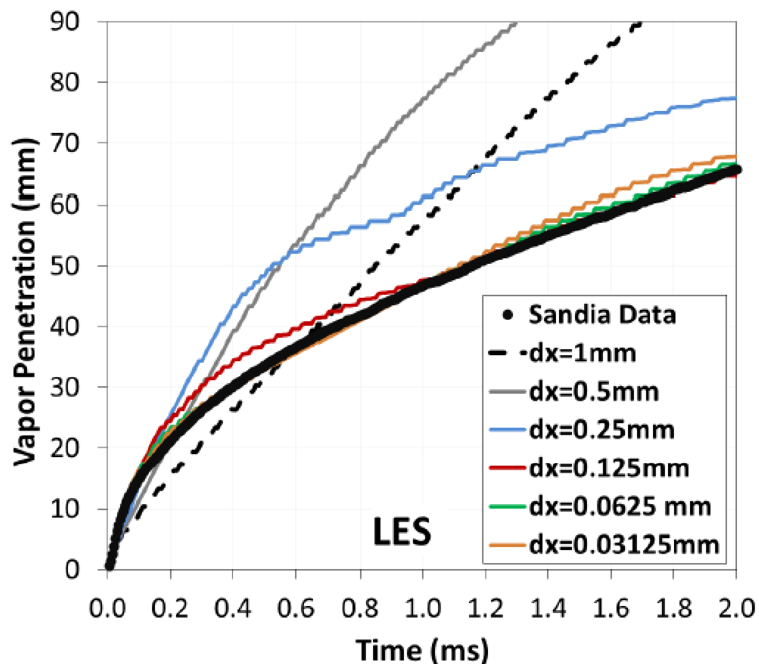
■ LES湍流模型

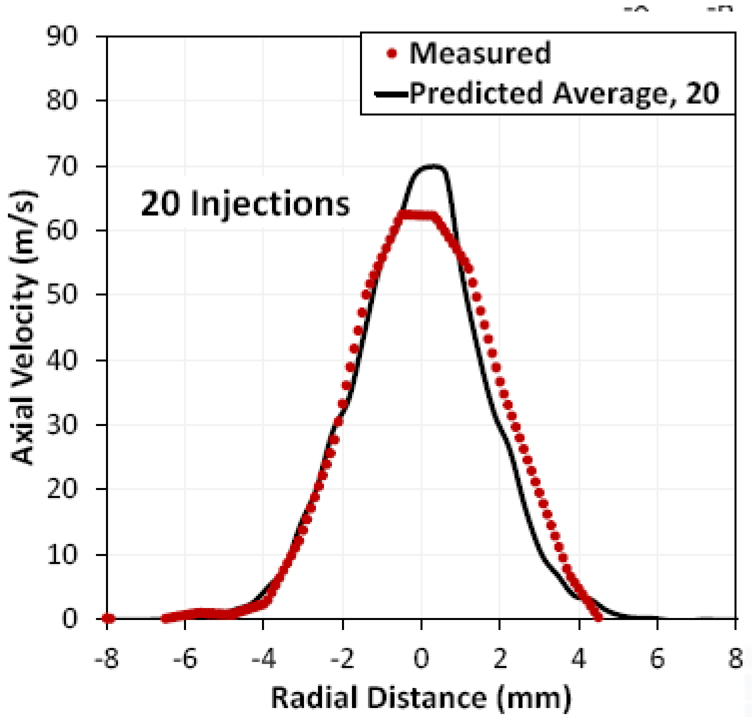




- 网格收敛的RANS结果也无法很好的和实验结果吻合
- LES结果可以很好的与实验吻合
- 这是由于LES模型求解更多的流动结构，于是可以更好的预测燃油和空气的混合
- Spray A的实验数据来源于Sandia National Lab的ECN

喷雾研究

LES湍流模型



Experimental data: Meijer et al., ICLASS 2012

Simulation results:

- Senecal and Som et al. ASME-ICEF2013-19082
- Xue and Som et al. AAS 2013

- 125 µm or finer resolutions necessary (recommend to use 62.5 µm)
- Multi-realization averaging is necessary to mimic experimental data (at least 10 realizations need to be averaged)

喷雾研究

CATERPILLAR

关键词： ECN、喷雾标定

喷雾研究

CATERPILLAR

- 对ECN喷雾的模拟测试
  - 通过优化标准k-e模型和RNG k-e模型参数得到和ECN Spray A测试相似的结果
  - 评估网格收敛性和网格方向敏感性

ECN

Comparison: Turbulence models

	Type	Model	Notes	Initialization
ANL	LES	Dynamic structure	20 flow realizations	Random seeds
CHALMERS	RANS	Standard k-ε	$C_1 = 1.55$, $\sigma_{eps} = 1.65$	Uniform k-ε
CMT	RANS	Standard k-ε	$C_1 = 1.6$, $\sigma_{eps} = 1.3$	Uniform k-ε
POLIMI	RANS	Standard k-ε	$C_1 = 1.55$, $\sigma_{eps} = 1.4$	Uniform k-ε
SANDIA	LES	Smagorinski	1 realization	Inflow generator

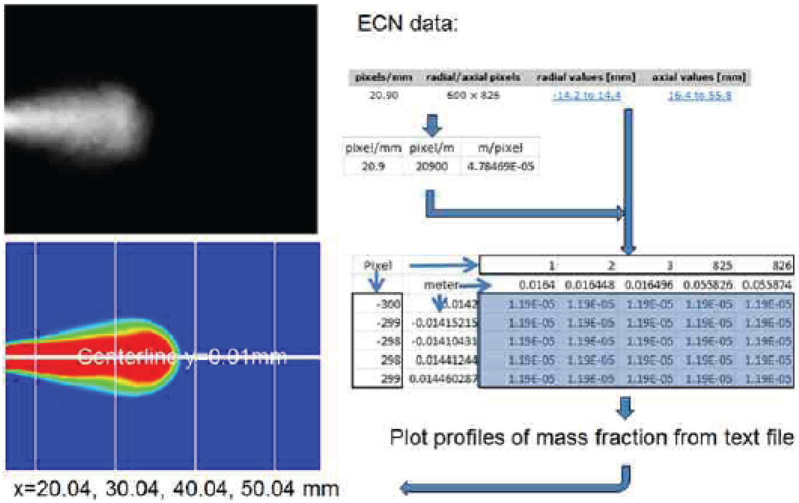
- Increasing C_1 in standard k-ε model is a common practice also used in simulation of turbulent gas jets (see past Proceedings of the SANDIA TNF workshop).
- LES/Lagrangian: initial flow field and particles generates fluctuations
- LES/Dense fluid: fuel inlet boundary condition generating fluctuations

Slide taken from ECN3 Proceedings , Topic 1.3: Evaporative Spray and Parametric Studies (www.sandia.gov/ECN/workshop/ecn3.php)

喷雾研究

CATERPILLAR

- 研究方法
  - 通过优化方法改变湍流及破碎模型参数
  - 与ECN Spray A测试结果比较
    - 液体贯穿距
    - 气体贯穿距
    - 混合质量分数分布



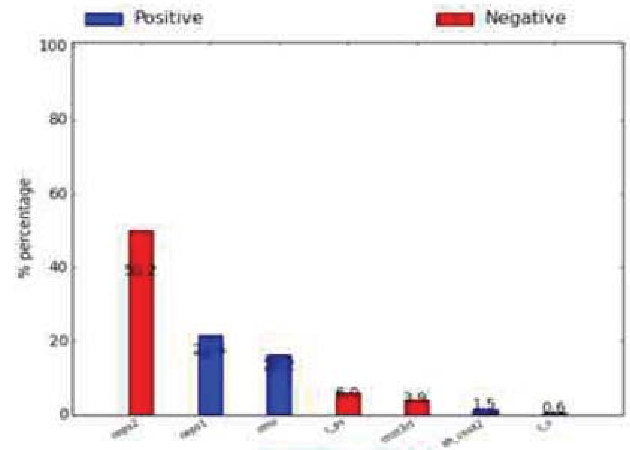
喷雾研究

CATERPILLAR

- 研究方法
  - 通过优化方法改变湍流及破碎模型参数

各参数取值范围

	kh_cnst2	cnst3rt	cmu	ceps1	ceps2	c_s	c_ps
min	5	0.1	0.08	1.4	1.6	0	0
max	9	1	0.1	1.6	2	2	0.2



各参数与贯穿距相关度

Observations:

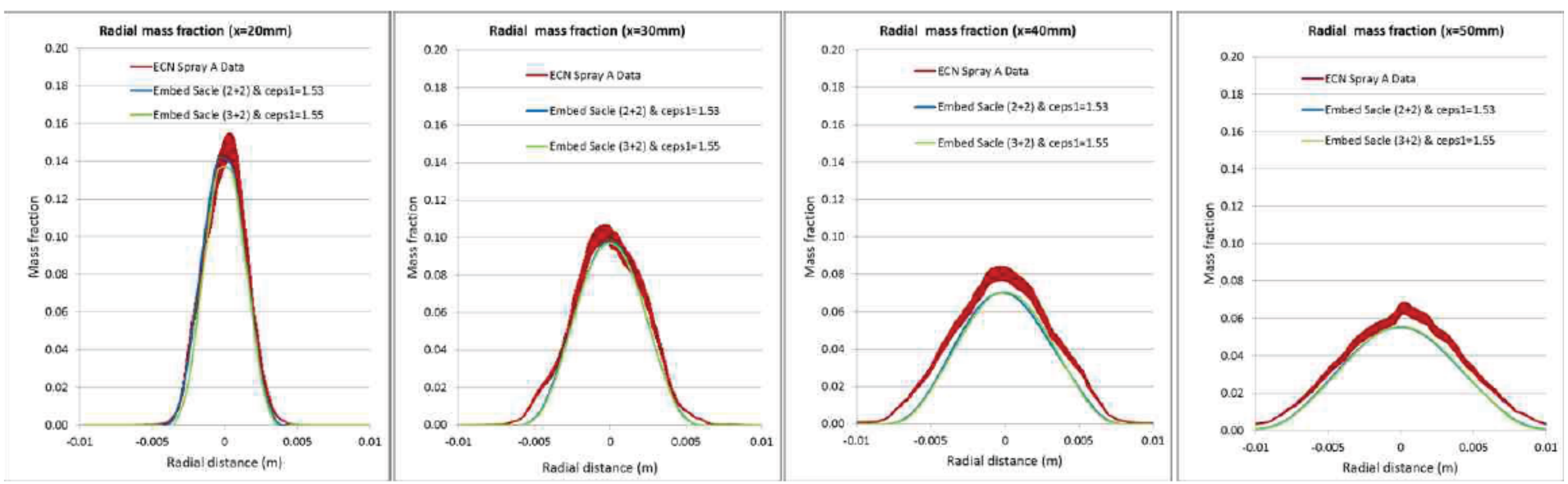
- $C_{\varepsilon 1}$ & $C_{\varepsilon 2}$ have greatest importance
- Optimized c_s & c_ps have greatest difference from standard practice, but low importance
- Standard k-ε model resulted in best agreement with experimental data

喷雾研究

- 研究方法
  - 改变网格加密形式及网格方向性研究
  - 同时关注并行数、random number seed对结果的影响

	Embed scale (2+2)	Embed scale (3+2)
Base grid	1.4mm	1.4mm
AMR Scale (temp/vel)	2	2
Zone 1 embed scale (grid size)	2 (0.35mm)	3 (0.0175mm)
Zone 2 embed scale (grid size)	2 (0.35mm)	2 (0.35mm)
Parcel#	fuel mass/1.5e-10	4x
radius_inject	1/2diam_noz	1/2diam_noz
penet_bin_size	0.000175	0.000175
Breakup model	default	default
Turbulence model	SKE + Adjust ceps1 only	SKE + Adjust ceps1 only

网格方案



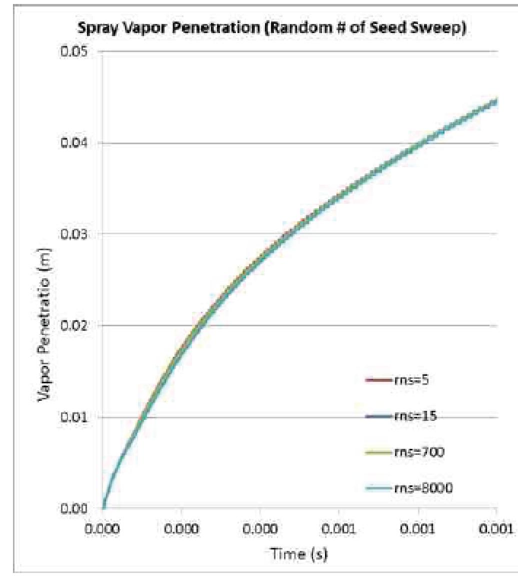
不同网格方案下，各位置的混合质量分数

喷雾研究

CATERPILLAR

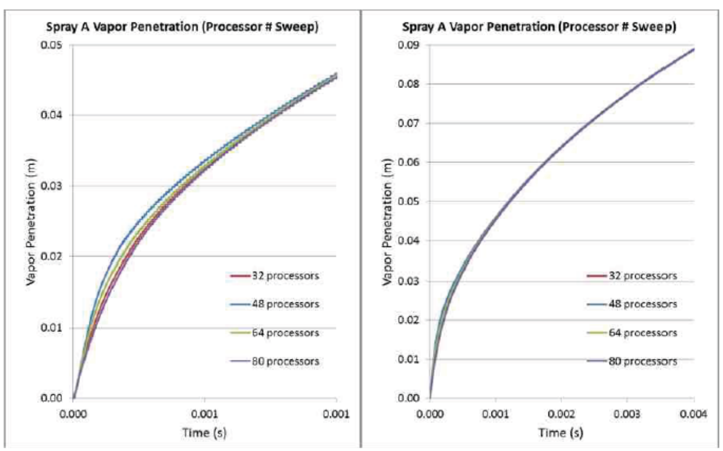
- 研究方法
  - 改变网格加密形式及网格方向性研究
  - 同时关注并行数、random number seed对结果的影响

Impact of Random Number Seed



随机数的影响

Near-Nozzle Penetration is impacted by the # of processors



近孔位置的贯穿距结果更易受并行影响

喷雾研究

关键词： JP-8、柴油机条件、RANS&LES

喷雾研究

- 美军要求JP-8适用于所有的空气及地面条件
- JP-8在柴油机喷射条件下的气化及油气混合过程研究
  - 喷射压力范围：200-2000bar
  - 环境条件：700-1100K，1-150bar

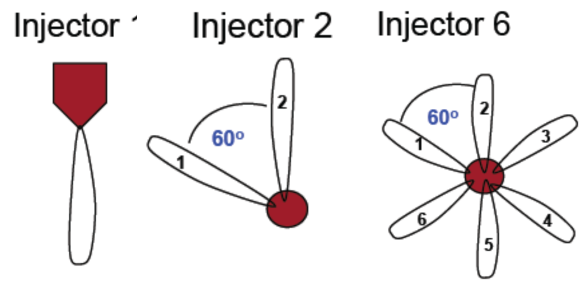
美国陆军装备司令部下属研究、开发和工程司令部

U.S Army Research Lab
陆军研究实验室

Compression-Ignition Engines

喷雾研究

- 柴油条件下多孔JP-8喷射油气混合形成过程的基础性及预测性仿真研究
  - RANS
    - 喷射常数，敏感性，燃油影响
  - LES
    - 替代燃油喷雾动力学影响
    - 多孔喷嘴的喷雾动力学影响



Exp Effort (Kurman/Tess[1])

- Perform detailed measurements in HTPV vessel at diesel engine conditions
- Characterization of single and multi-hole injection quantities and spray parameters
- Establish experimental database for model validation

Computational Effort (Bravo[2,3])

- Investigate engineering spray breakup models for prediction of liquid/vapor lengths
- RANS/LES computation of spray at HTPV vessel conditions considering various surrogate fuels for JP-8
- RANS/LES computation with SH MH injector configurations

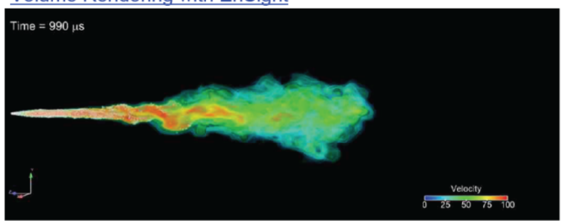
CFD仿真工具：CONVERGE

喷雾研究

US ARMY RDECOM ARL

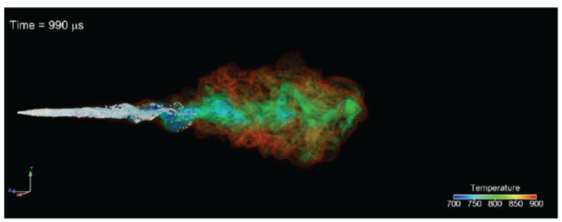
■ 结果

Volume Rendering with EnSight



Velocity Conditions
Injected mass = 7.5 mg
diameter = 147 um

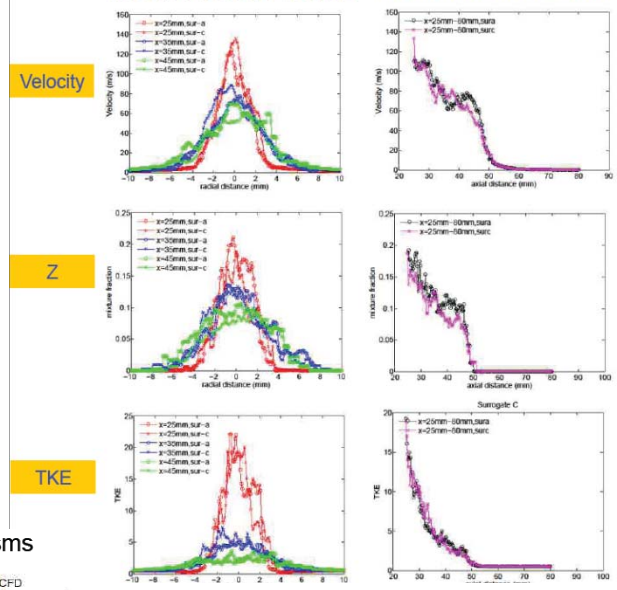
quiescent environment



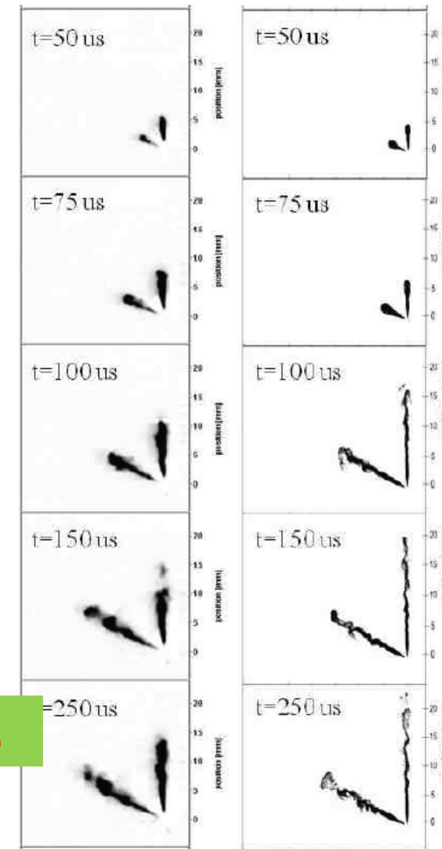
Temperature Conditions
Injected mass = 7.5 mg
diameter = 147 um

T (ambient) = 900 K
T (injection) = 373 K

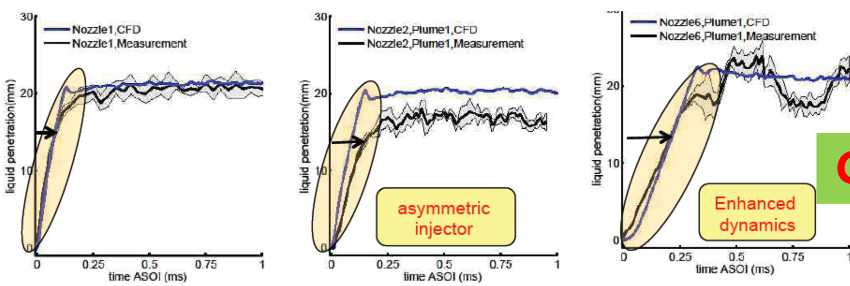
Mean Radial Profiles　Mean Axial Profiles



Mie/Schlieren　CFD



Clear distinctions among all spray parameters due to various mechanisms



CFD仿真工具：CONVERGE

主要内容

- 流动特性
- 喷雾研究
- 燃烧系统

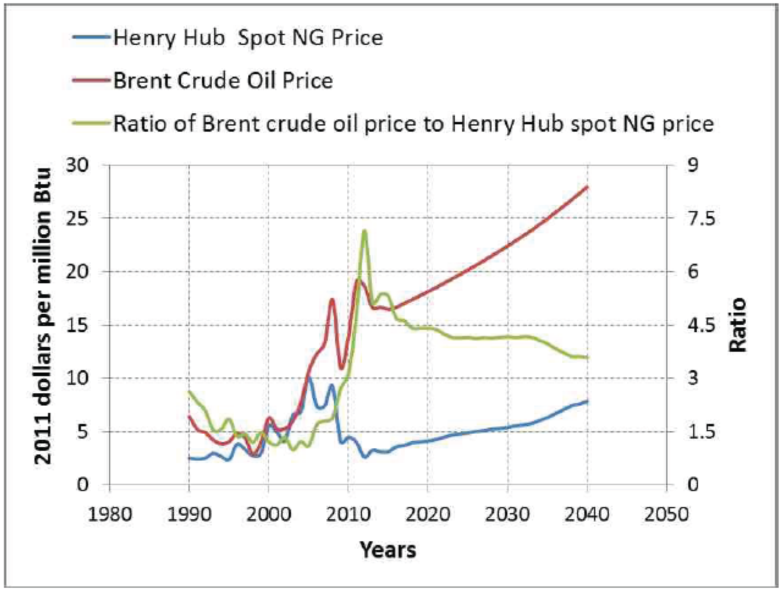
燃烧系统

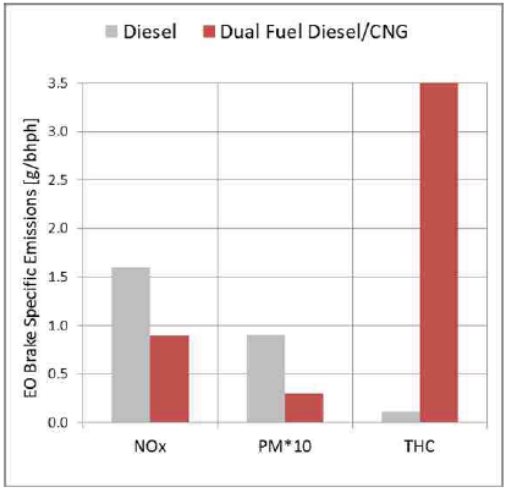
FEV

关键词： 双燃料、RCCI、重载

燃烧系统

- 重载柴油机中柴油-天然气RCCI燃烧评估
  - 双燃料较柴油具有经济性、低排放优势

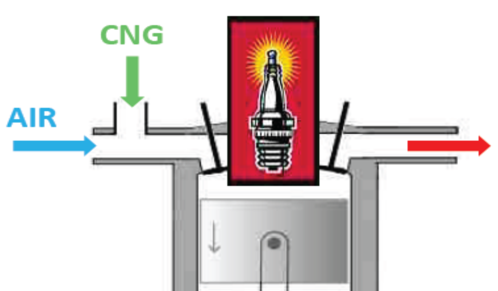




燃烧系统

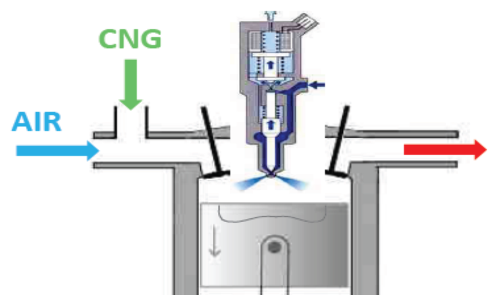
- 重载柴油机中柴油-天然气RCCI燃烧评估
  - 理论配比 vs 双燃料

Stoichiometric Spark Ignited



Pro	Con
• Single Fuel • TWC • Low Cost Fuel System	• Knock Limit • Max Load • Lower Efficiency • Ignition System • CH_4 Emissions • NH_3 Emissions

Dual Fuel Compression Ignited



Pro	Con
• Max Load • Lean Operation • BSFC/CO2 • Infrastructure Independence • Retrofit	• NOx Aftertreatment • DPF required • Two Fuels • Fuel System and ATS Cost • CH_4 Emissions

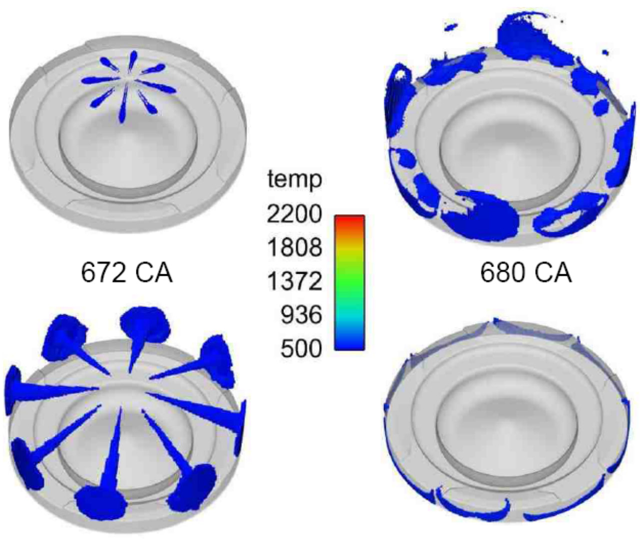
燃烧系统

- CFD研究目的
  - 理解RCCI的燃烧过程及缸内条件
  - 理解和解释双燃料RCCI技术的HC和CO排放局限
  - 进一步应用到更高载荷工况下，拓展RCCI应用范围

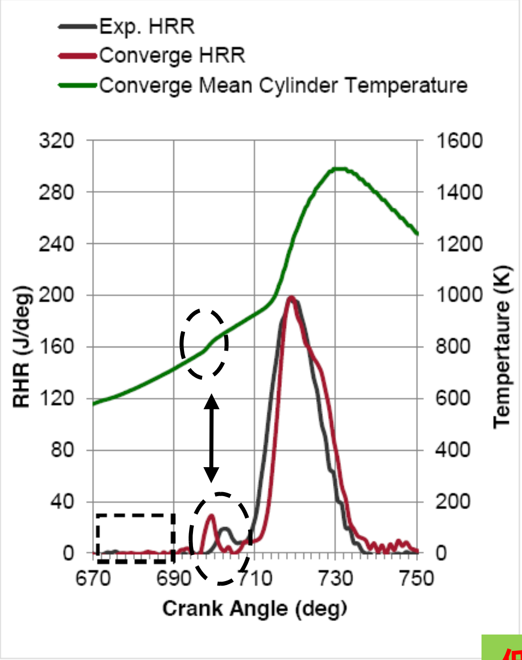
燃烧系统

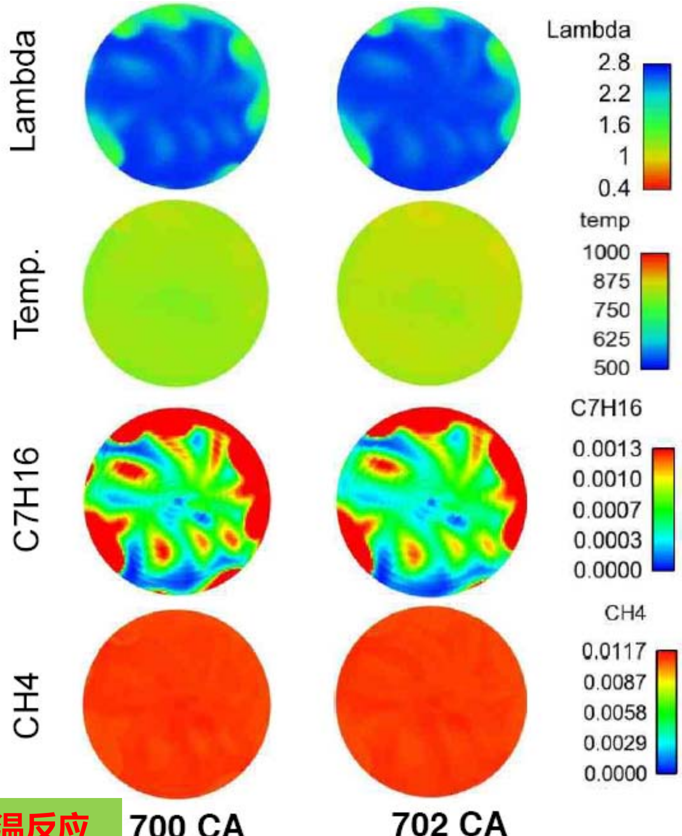
- RCCI燃烧结果
  - 喷雾及混合
  - 低温反应

IsoVolume Plots (λ ≤ 1)



喷雾及混合

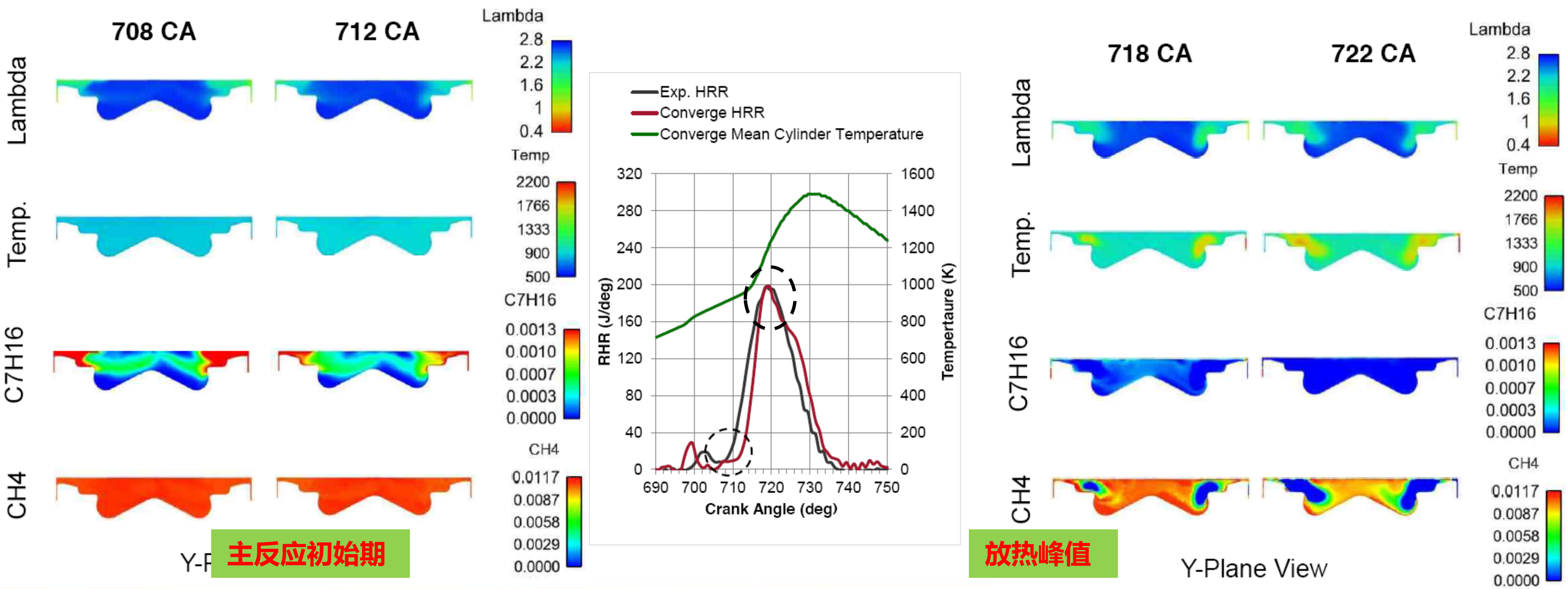




低温反应

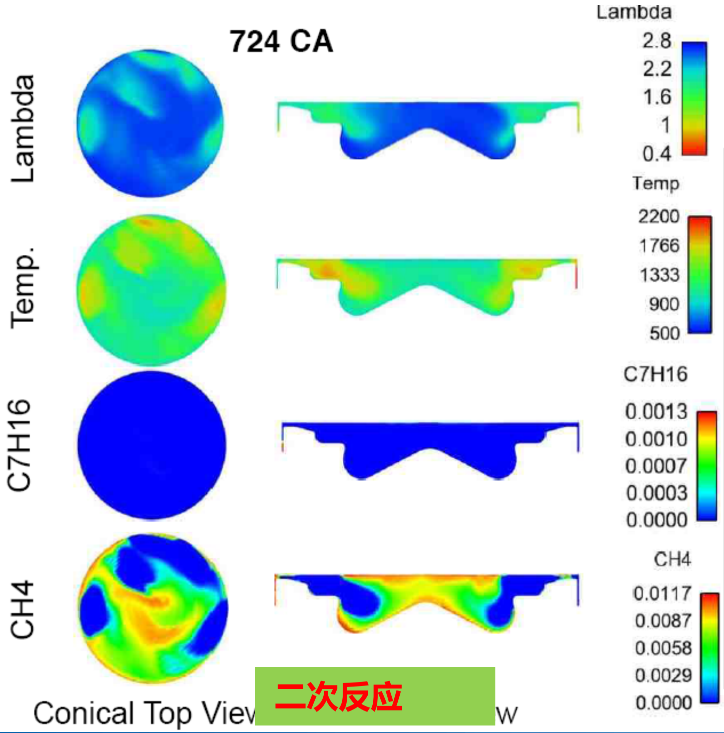
燃烧系统

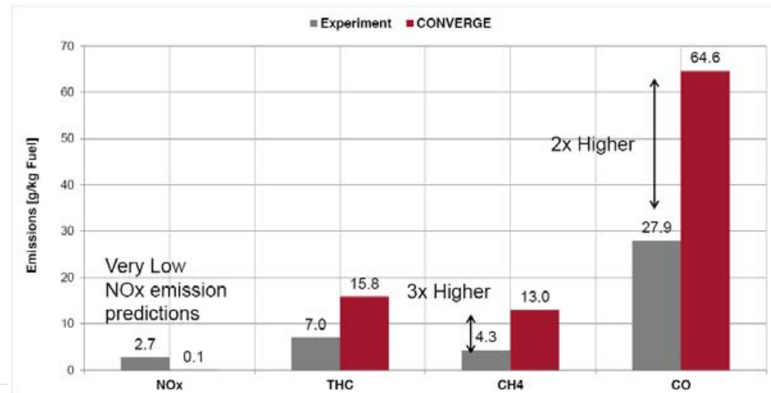
- RCCI燃烧结果
  - 主反应初始期
  - 放热峰值

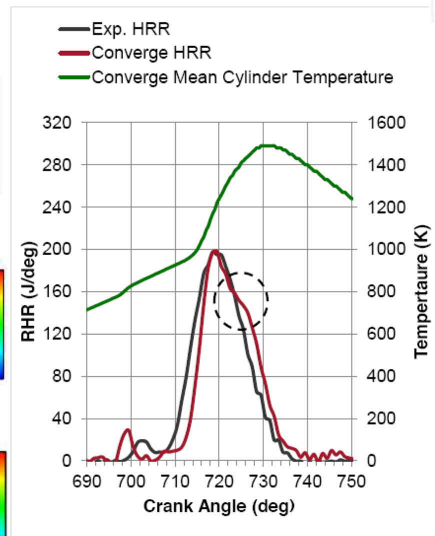


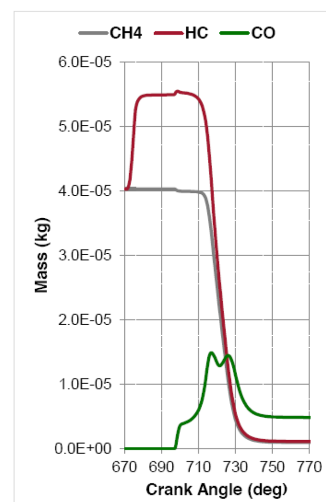
燃烧系统

- RCCI燃烧结果
  - 二次反应
  - 排放









排放预测

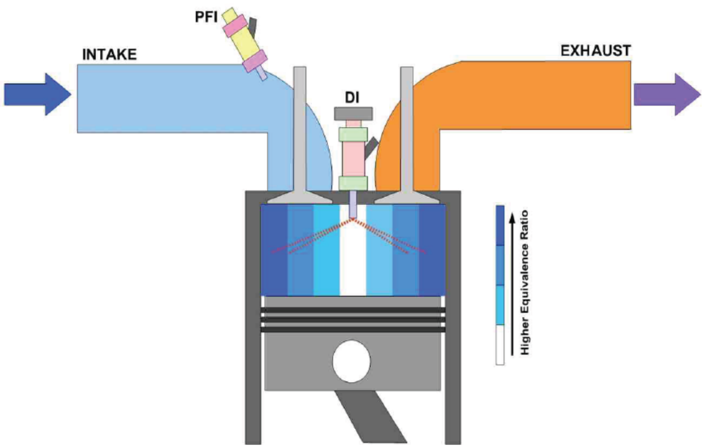
燃烧系统

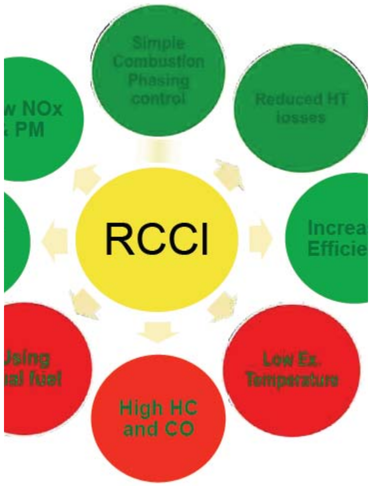
关键词： 双燃料、RCCI

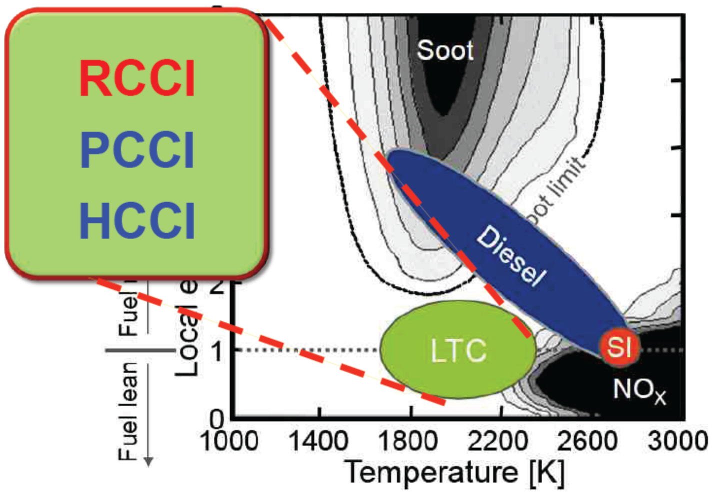
燃烧系统

EML

密歇根理工大学
能源机电一体化实验室







Source: Gurpreet Singh, Overview of the 2011 DOE Advanced Combustion Engine R&D.

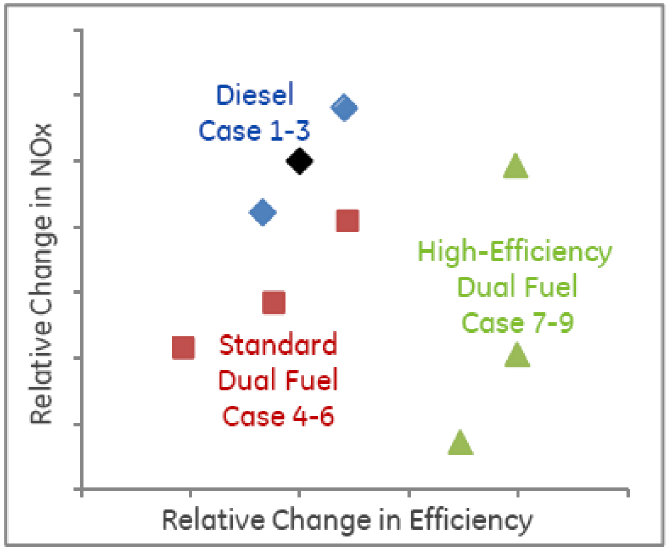
NOx (g/kg-fuel)		HC (g/kg-fuel)		CO (g/kg-fuel)		CO2 (g/kg-fuel)	
Exp.	Sim.	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
0.61	0.04	63.74	53.86	64.59	41.84	2847.70	3005.69

燃烧系统

关键词： 双燃料、工况标定、HEDF

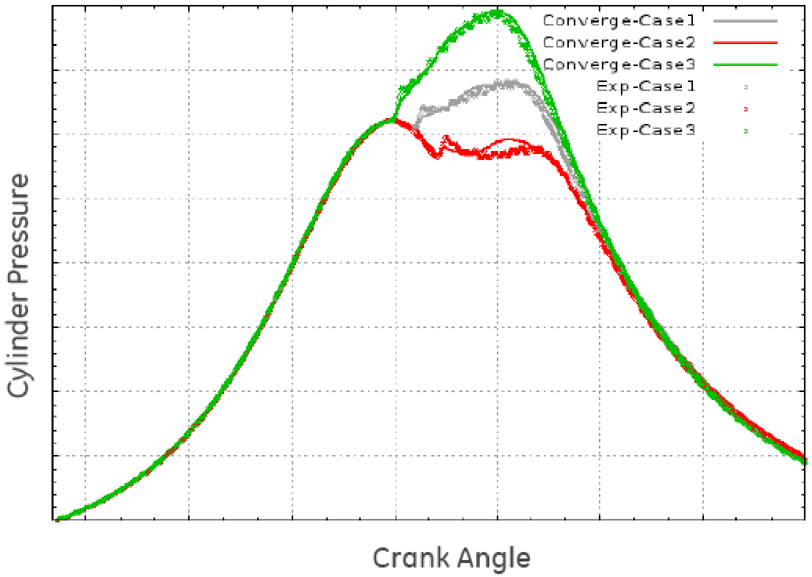
燃烧系统

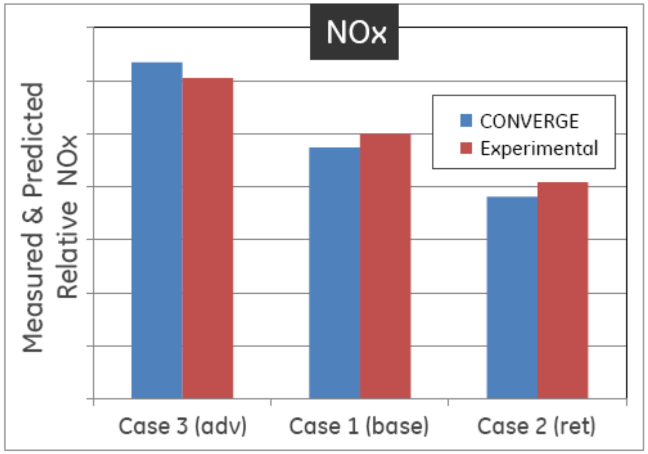
- 双燃料燃烧CFD模拟
  - 目标及现状
    - 100%柴油和标准双燃料（StDF）工况下已实现能达到标定状态的先进CFD仿真架构
    - 致力于对高效双燃料（HEDF）工况的进展

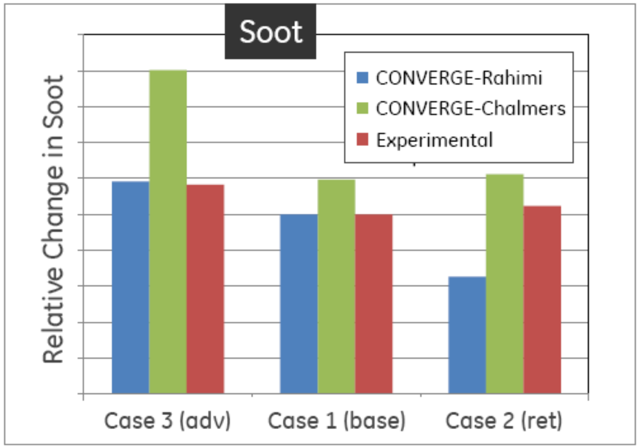


燃烧系统

■ 100%柴油



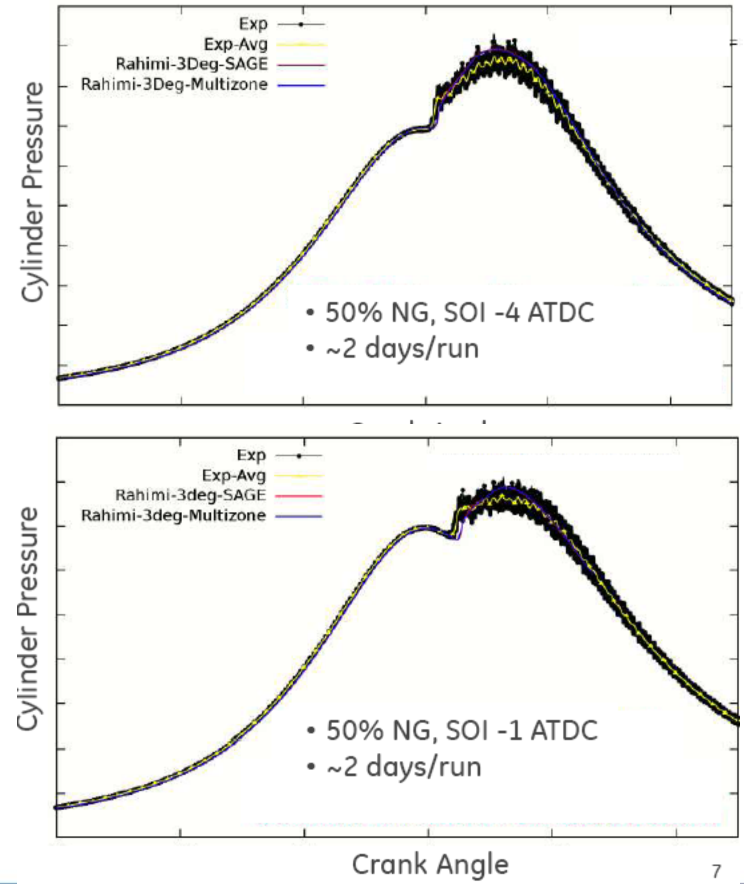




Injection Timing Swing
- Case1 = center point
- Case2 = retarded
- Case3 = advanced

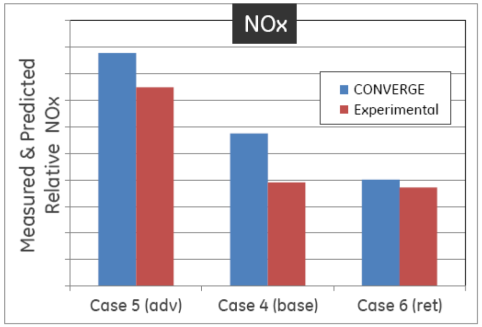
燃烧系统

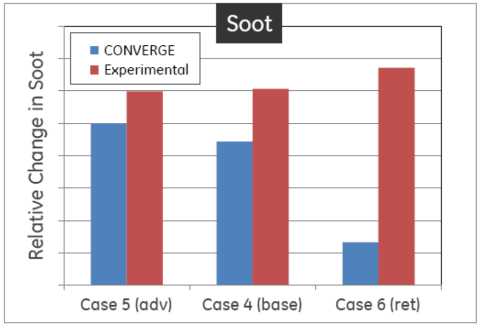
- StDF
  - 缸压规律捕捉很好
  - SOI影响捕捉很好
  - 循环变动
  - 机理比较
    - Lawrance-Livermore
    - Rahimi

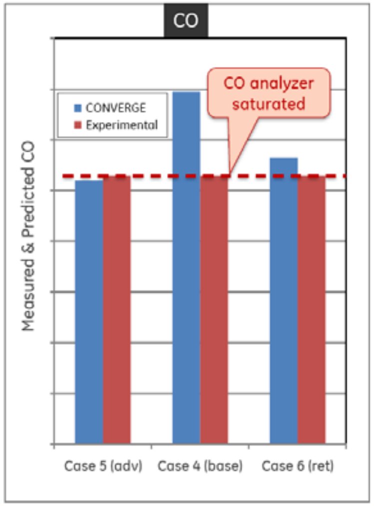


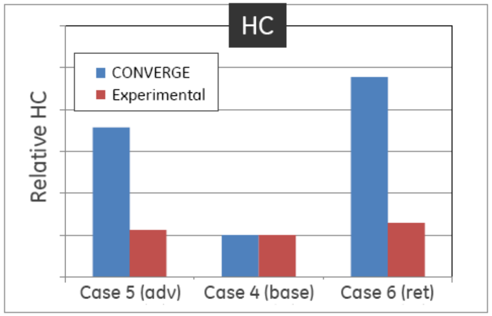
燃烧系统

- StDF
  - 排放预测局限
    - 循环变动
    - 化学反应机理
    - 多区域划分
    - 实验测量错误



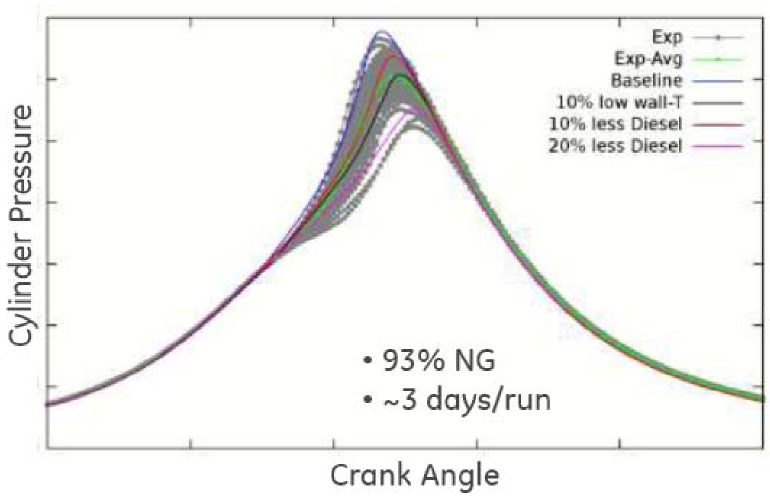


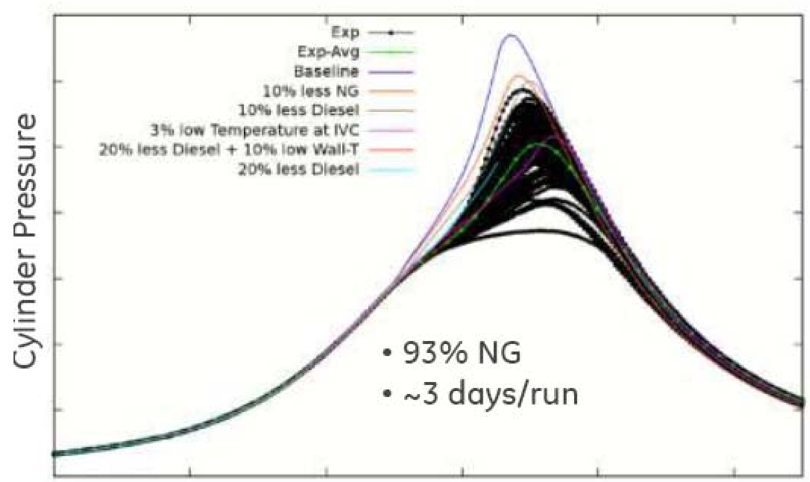




燃烧系统

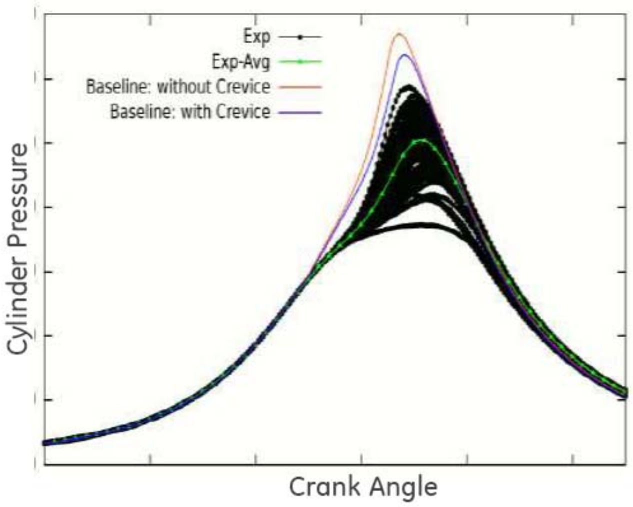
- HEDF
  - 循环变动
    - 不稳定/嘈杂的燃烧过程
    - 喷油量和壁温引发变化

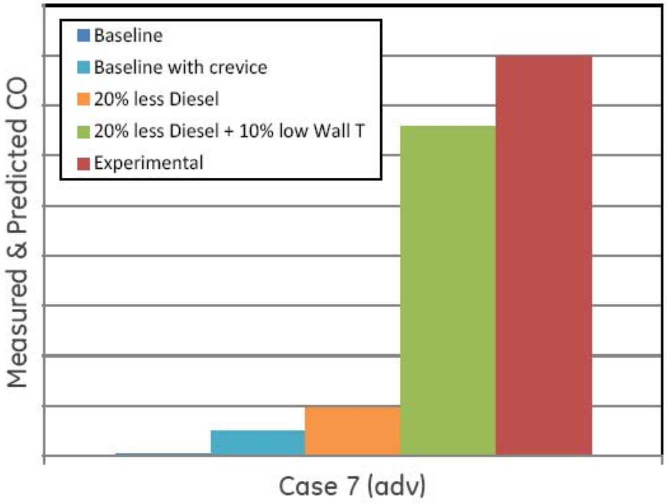




燃烧系统

- HEDF
  - 活塞环模拟
    - 缸压及CO预测趋势正确
    - 细化模型
    - 计算资源





燃烧系统

关键词： 双燃料、非受控燃烧、喷油策略

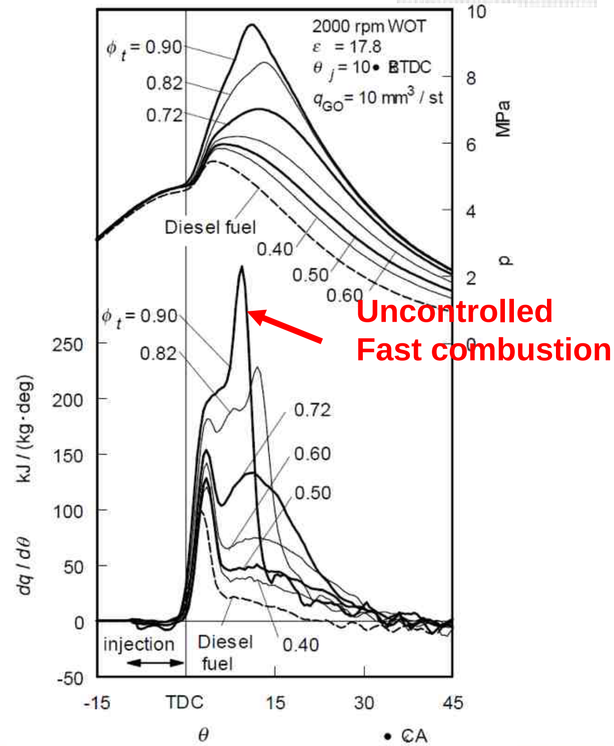
燃烧系统

Colorado State University

ENGINES AND ENERGY CONVERSION LABORATORY

- 柴油-天然气双燃料发动机非受控燃烧速率研究
  - 预测不同喷油时刻的压力及放热率
  - 非受控燃烧发生位置
  - 非受控燃烧成因（upcoming）

Case Name	D25G17				D12G22				D12G22P2
Engine Speed (RPM)	2200				2200				2200
Injected diesel per cylinder (mg)	25.4				12.1				11.7
Natural gas per cylinder (mg)	16.5				21.8				22.1
Additional Propane (mg)	0				0				2.3
Natural gas energy share (%)	43.3				67.9				71.9
Start of injection (deg. ATDC)	-8.8	-10	-12	-13	-8	-10	-12	-14	-10
Boost Pressure (kPa abs)	169.3	167.9	166.6	167.2	168.2	168.5	164.9	163.6	163.0
Net IMEP (bar)	15.0	15.1	15.6	15.6	10.9	10.7	10.6	10.7	11.7

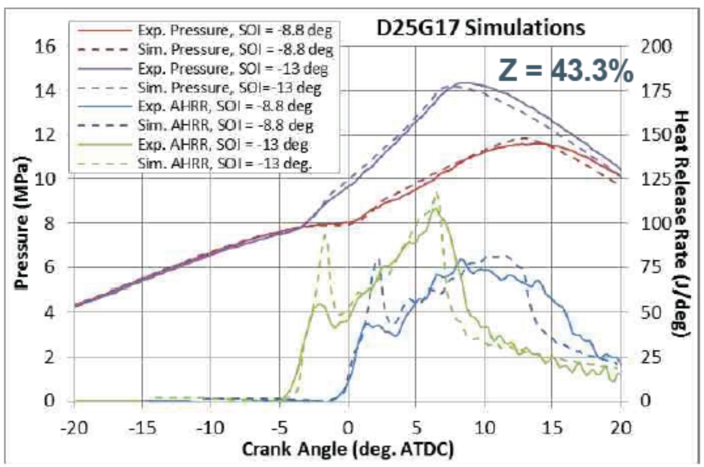


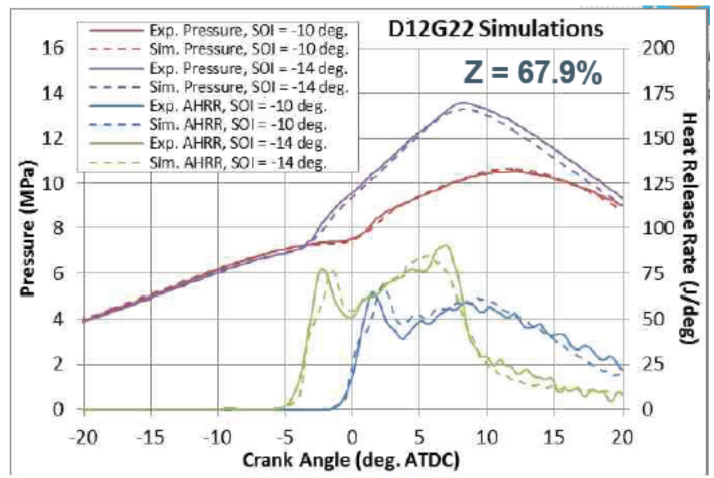
燃烧系统

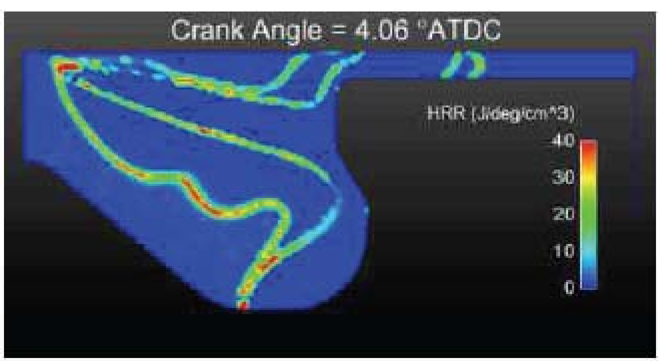
Colorado State University

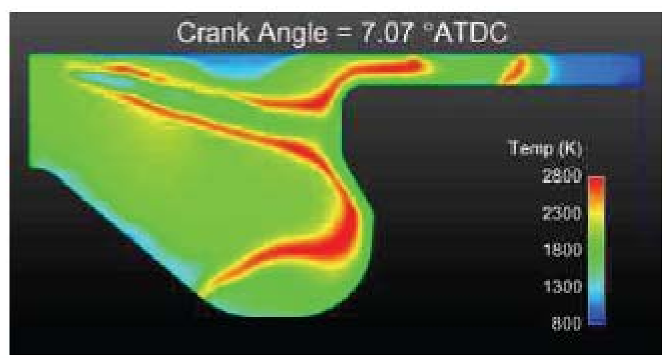
ENGINES AND ENERGY CONVERSION LABORATORY

- 喷油时刻策略实验及仿真结果







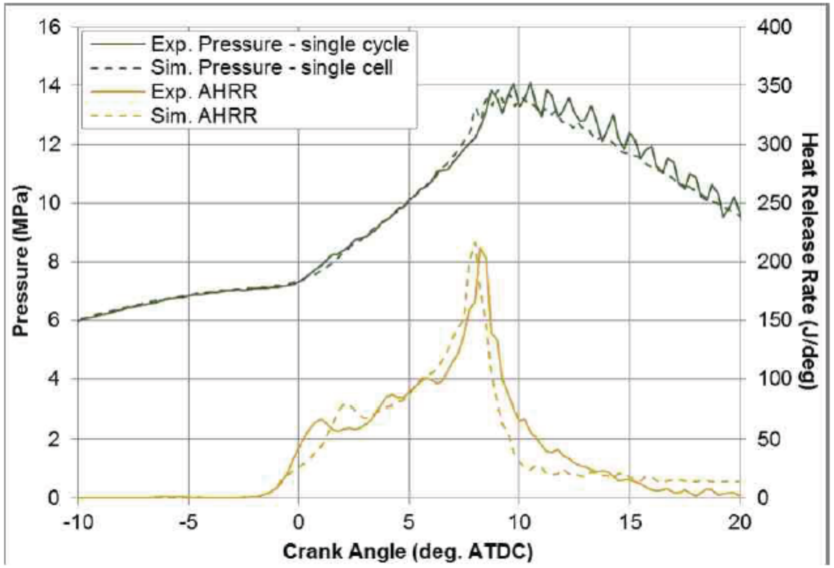


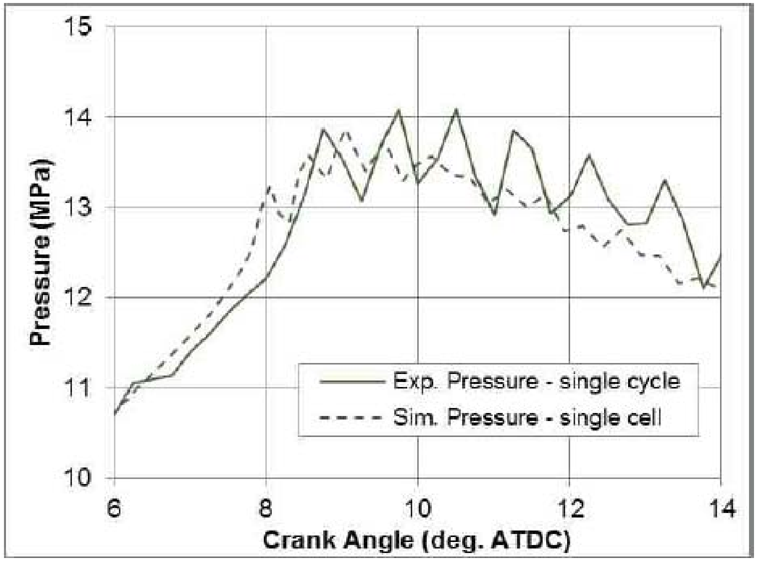
燃烧系统

Colorado State University

ENGINES AND ENERGY CONVERSION LABORATORY

丙烷添加





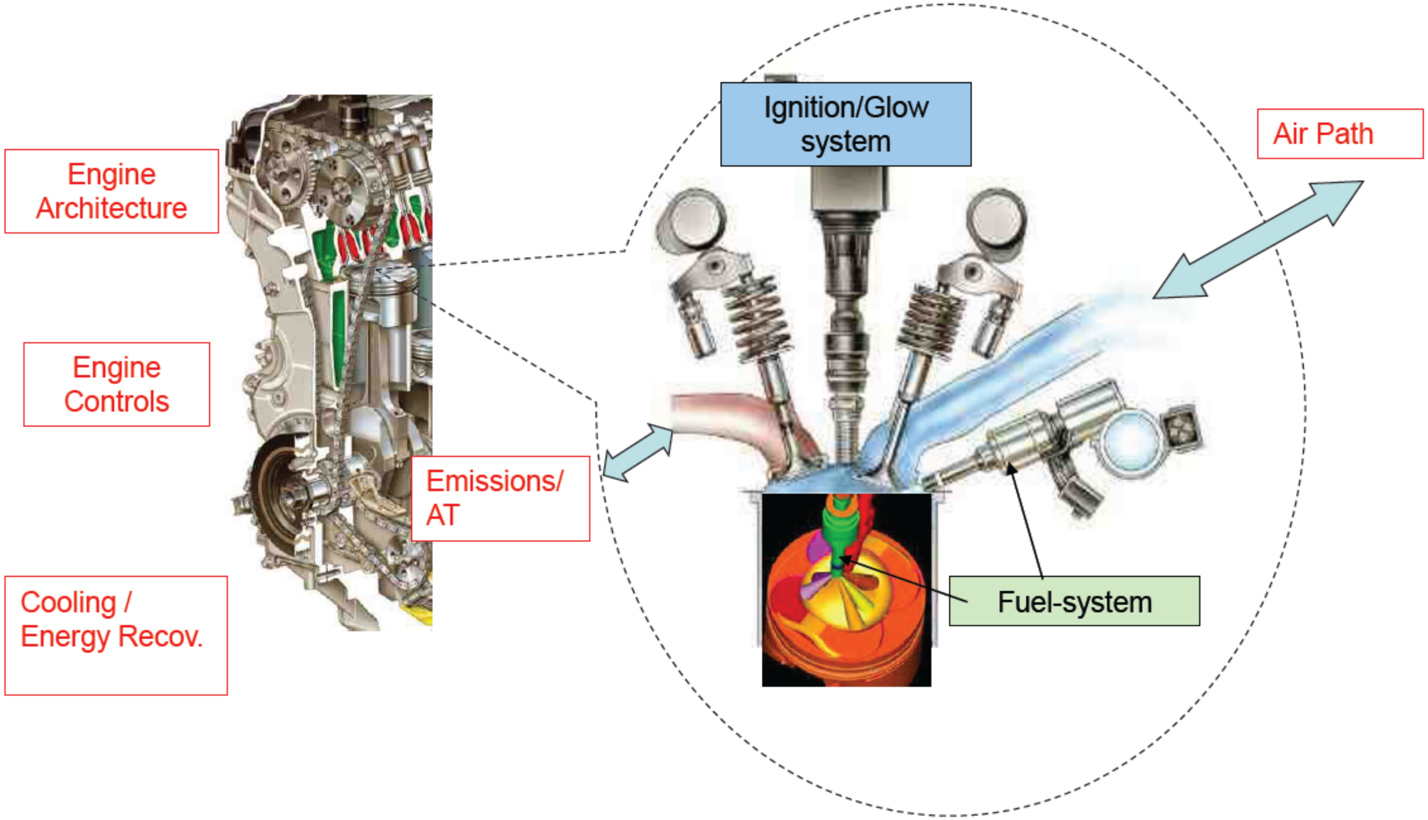
CONVERGE™ model was able to predict **uncontrolled fast combustion rates** in the **propane addition** case and was able to show **pressure waves** with similar frequency but reduced magnitude

燃烧系统

关键词： 稀薄燃烧、敲缸、soot、SI颗粒

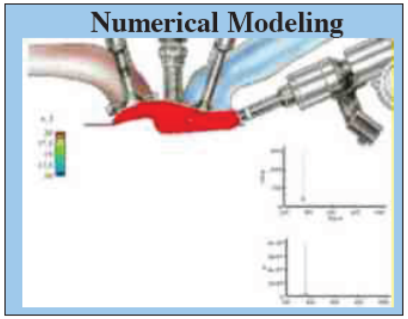
燃烧系统

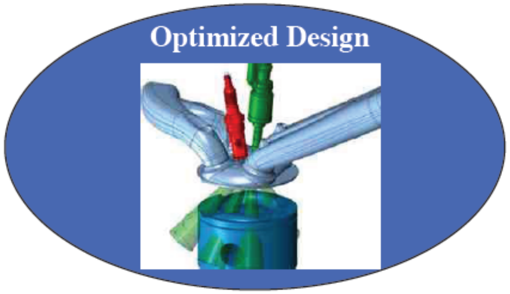
- CFD仿真应用于发动机开发的各个方面

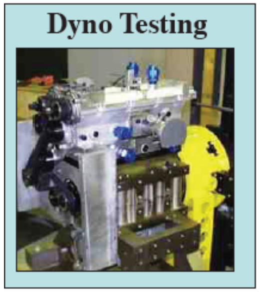


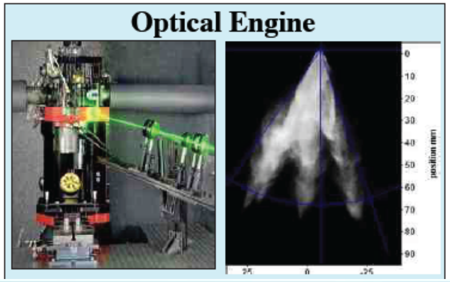
燃烧系统

- 综合性前沿燃烧系统优化方法









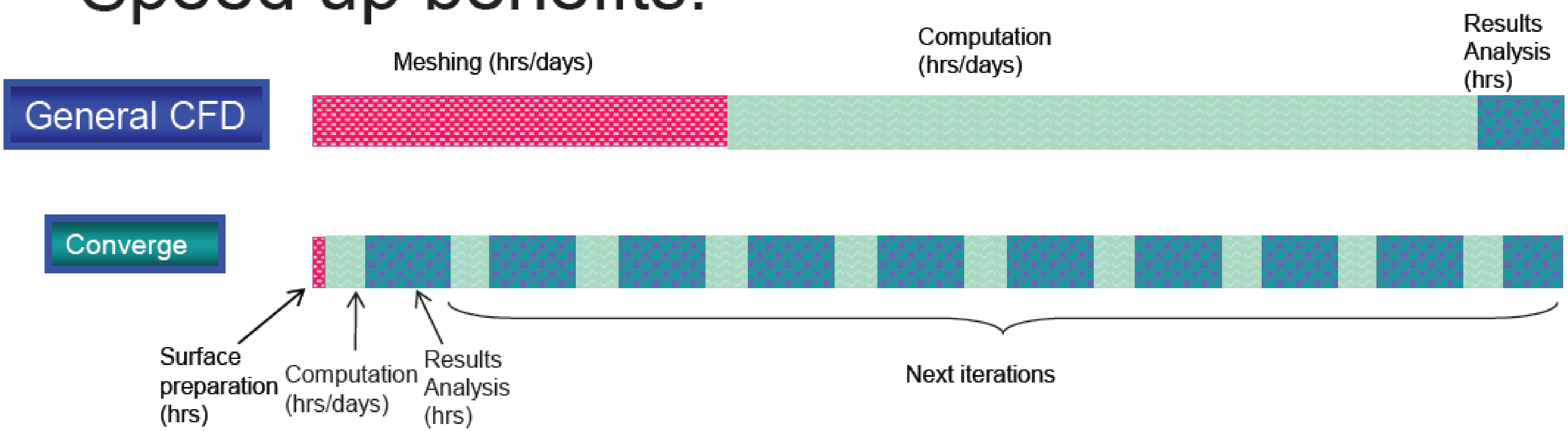
整合了CFD仿真，光学实验及台架实验

CFD仿真代码平衡了内部研发和用户友好、高并行效率、自动化网格的商业软件

燃烧系统

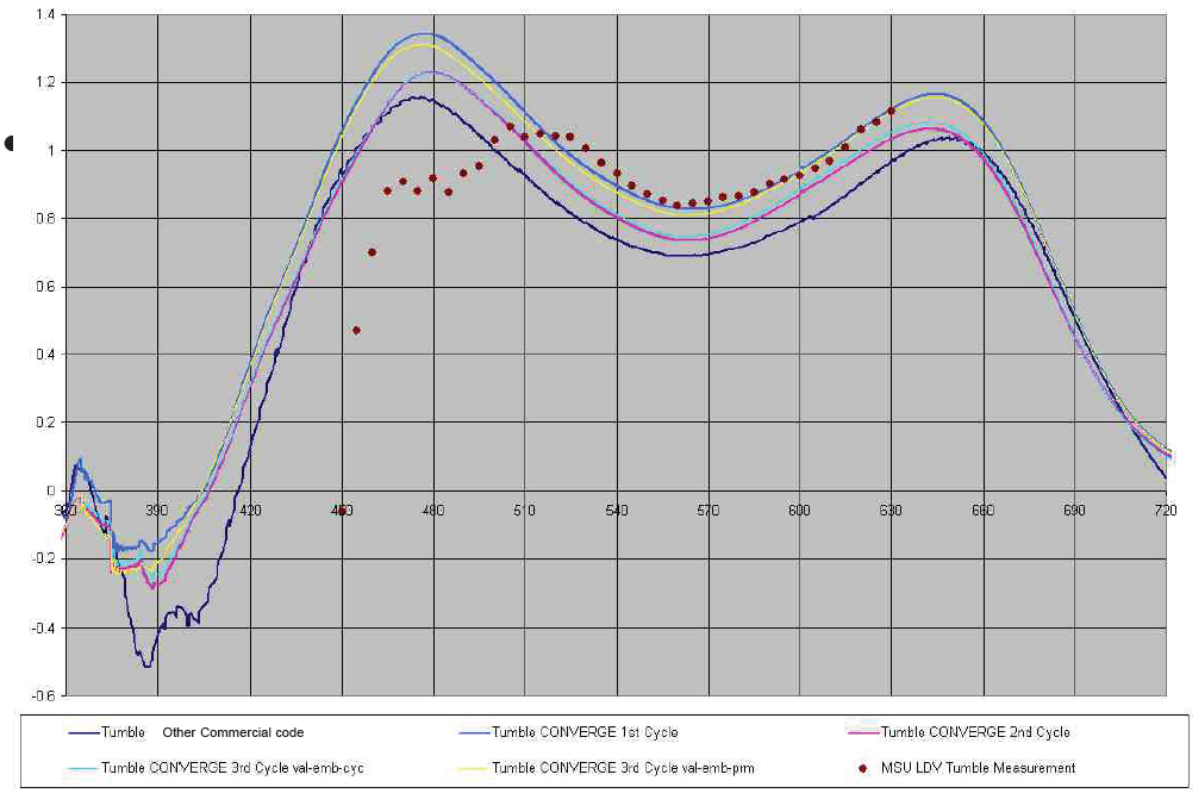
- CONVERGE在研发系统中的应用
  - Zero-Meshing

Speed up benefits:



燃烧系统

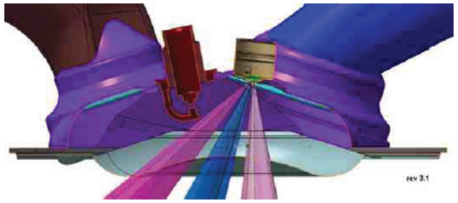
- CONVERGE在研发系统中的应用
  - 模型验证：流动预测



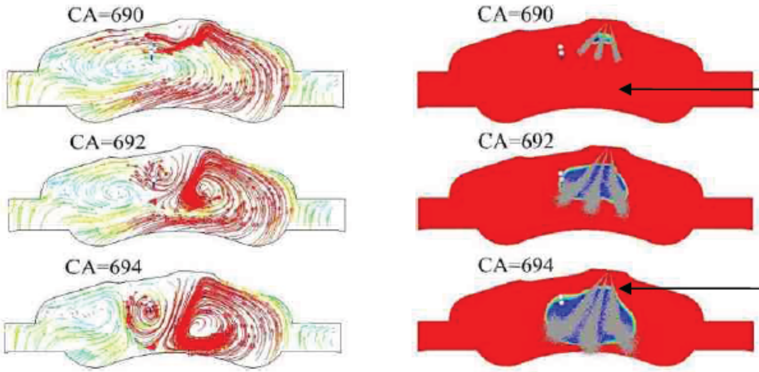
燃烧系统

- CONVERGE在研发系统中的应用
  - 设计和研发先进的稀薄燃烧系统
  - 优化目标

Combustion System – Section View



Air Flow & Air / Fuel Spatial
& Temporal Evolution



“Micro” Stratified Charge

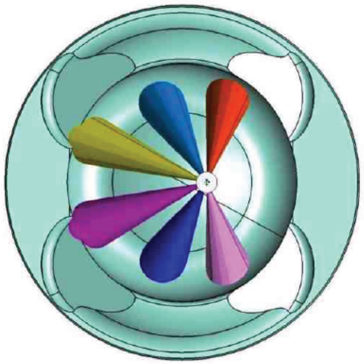
=

- Overall Lean Homogeneous
- Early Primary Injection
- Air / Fuel ~ 20-30:1

\+

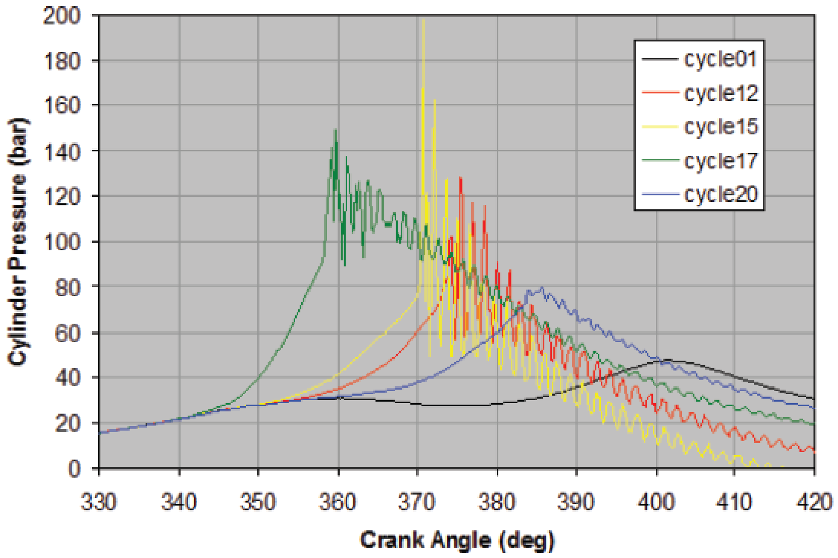
- Locally Rich Stratified
- Late Secondary Injection
- “Micro” Second Pulsewidth

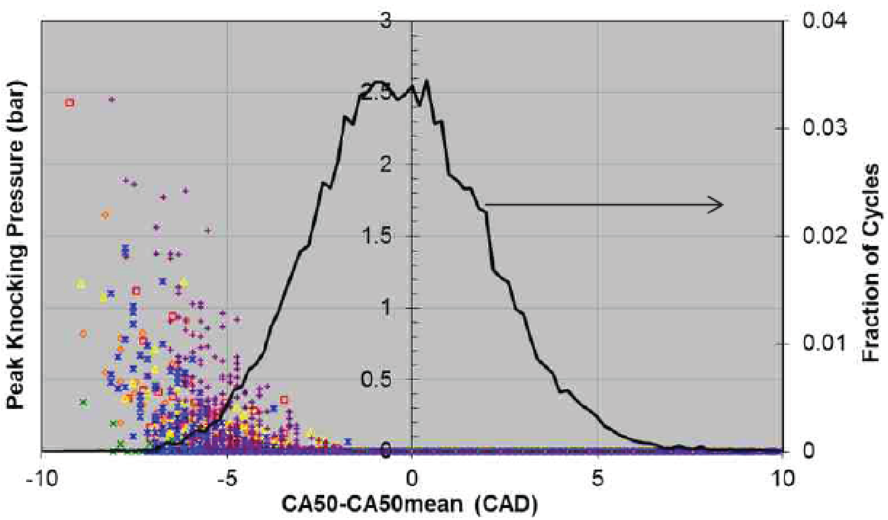
Combustion System – Plan View



燃烧系统

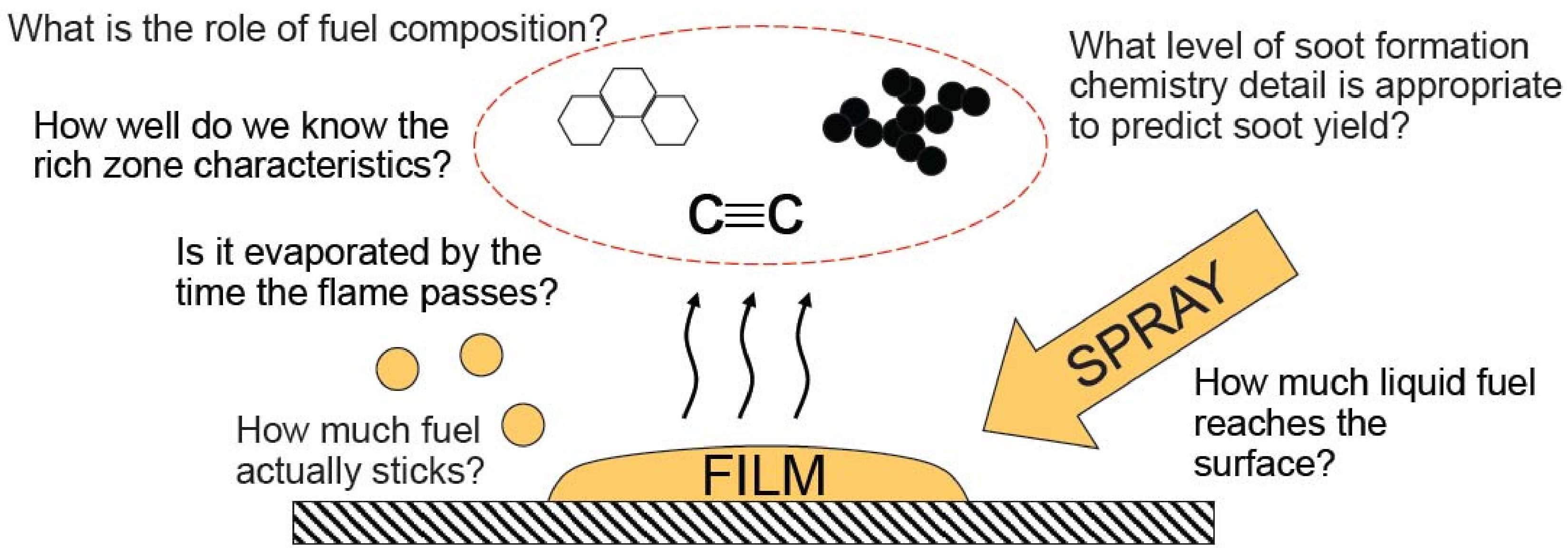
- 未来的技术挑战
  - 通过降低循环变动来减轻敲缸
  - 喷嘴内部流动及雾化对燃气混合的影响





燃烧系统

- 未来的技术挑战
  - DI发动机SOOT形成
  - SI颗粒的形成



To model PM, we will need to accurately answer a number of open questions.

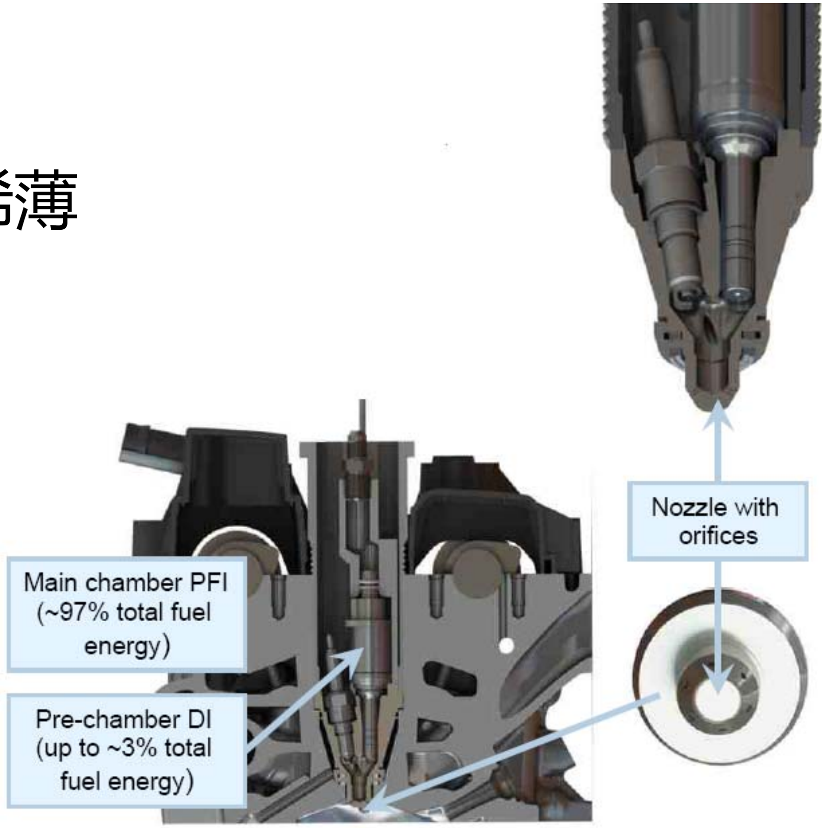
燃烧系统

MAHLE

关键词： 超稀薄燃烧、TJI

燃烧系统

- 超稀薄燃烧发动机湍流射流点火系统（TJI）
  - 高效、清洁
  - TJI提供分布式点火引发超稀薄燃烧
  - 预燃室结构特征



燃烧系统

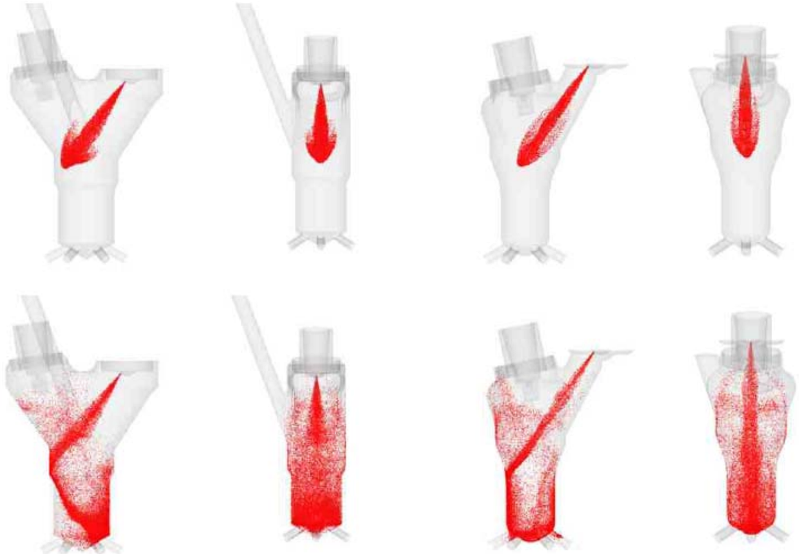
- TJI燃烧系统CFD模拟
  - 利用CONVERGE进行实验工况点对比计算
  - 辅助原型预燃室的设计开发
  - 提供预燃室内混合发展过程
  - 探索喷孔几何及预燃室结构影响
  - 湍流点火过程基础燃烧分析

MAHLE

- ❑ RANS assumptions to model the effect of turbulence in the reactive flow domain
- ❑ Detailed chemistry to model the combustion using a 38-species, 69 reaction gasoline surrogate (iso-octane) skeletal reaction mechanism
- ❑ Grid size can dynamically vary from 4 mm to 0.125 mm throughout the domain
- ❑ AMR strategy available in the Converge code is used to embed cells of 0.125 mm at the high temperature boundary.

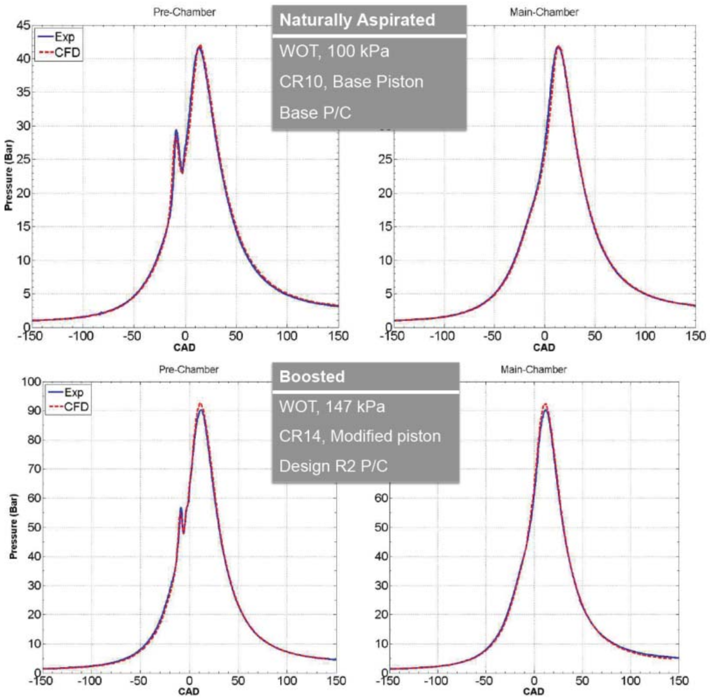
燃烧系统

- CONVERGE计算结果
  - 压力对比
  - 辅助燃油直喷



Base P/C

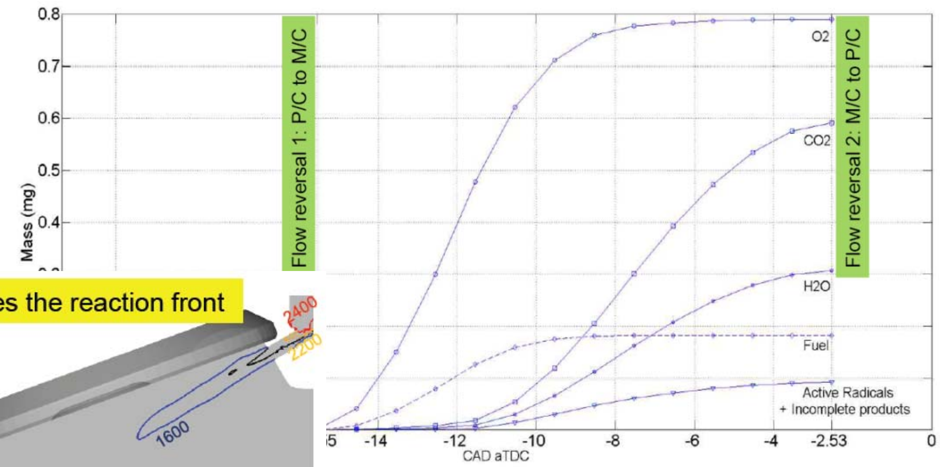
DesignR2 P/C



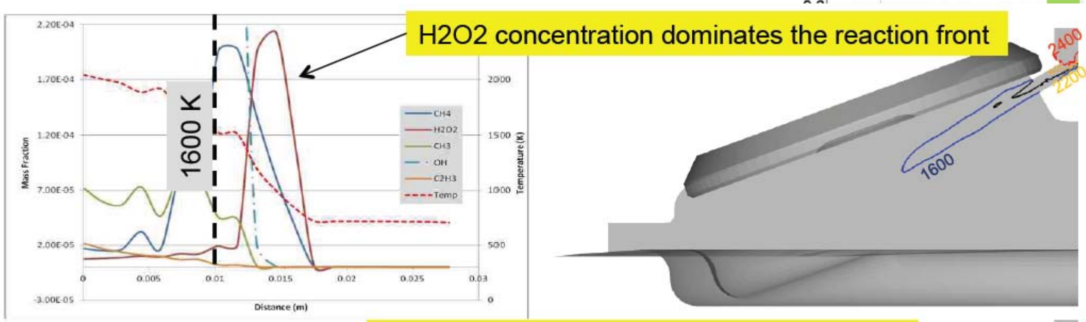
燃烧系统

MAHLE

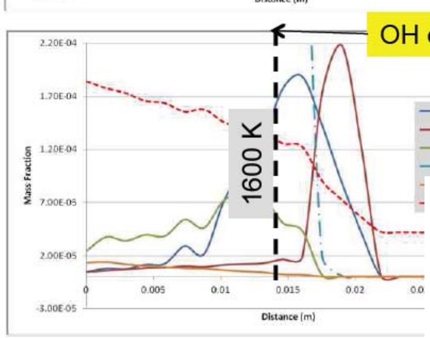
- CONVERGE计算结果
  - 组分分析

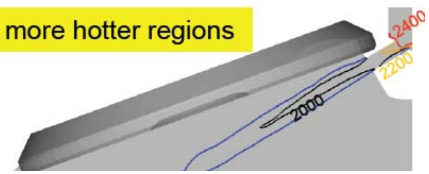


-10 aTDC



-9 aTDC





Further analysis results will be presented as:

"***RANS based multidimensional modeling of an ultra-lean burn pre-chamber combustion system with auxiliary liquid gasoline injection***" for SAE World Congress 2015

燃烧系统

IUPUI

关键词： TJI、定容燃烧

燃烧系统

IUPUI

印第安纳大学与普渡大学印第安纳波利斯联合分校

- 定容燃烧器预燃室热喷射点火模拟

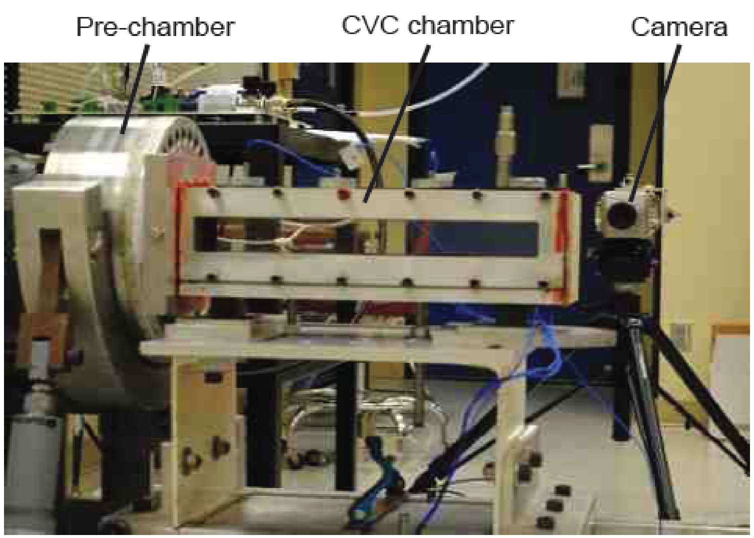


Figure . Constant-volume combustor ignition rig

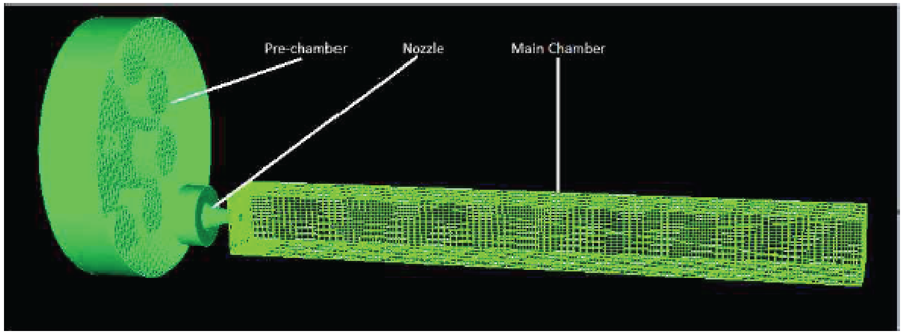


Figure . 3-D Computational domain and initial mesh

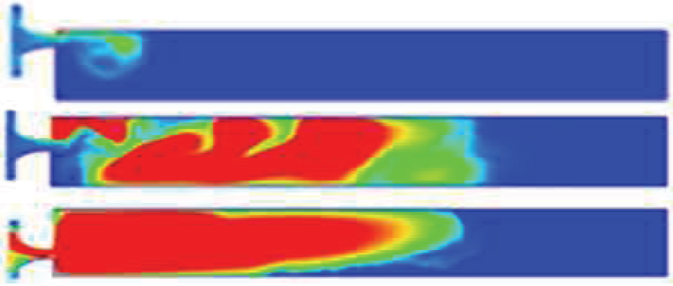
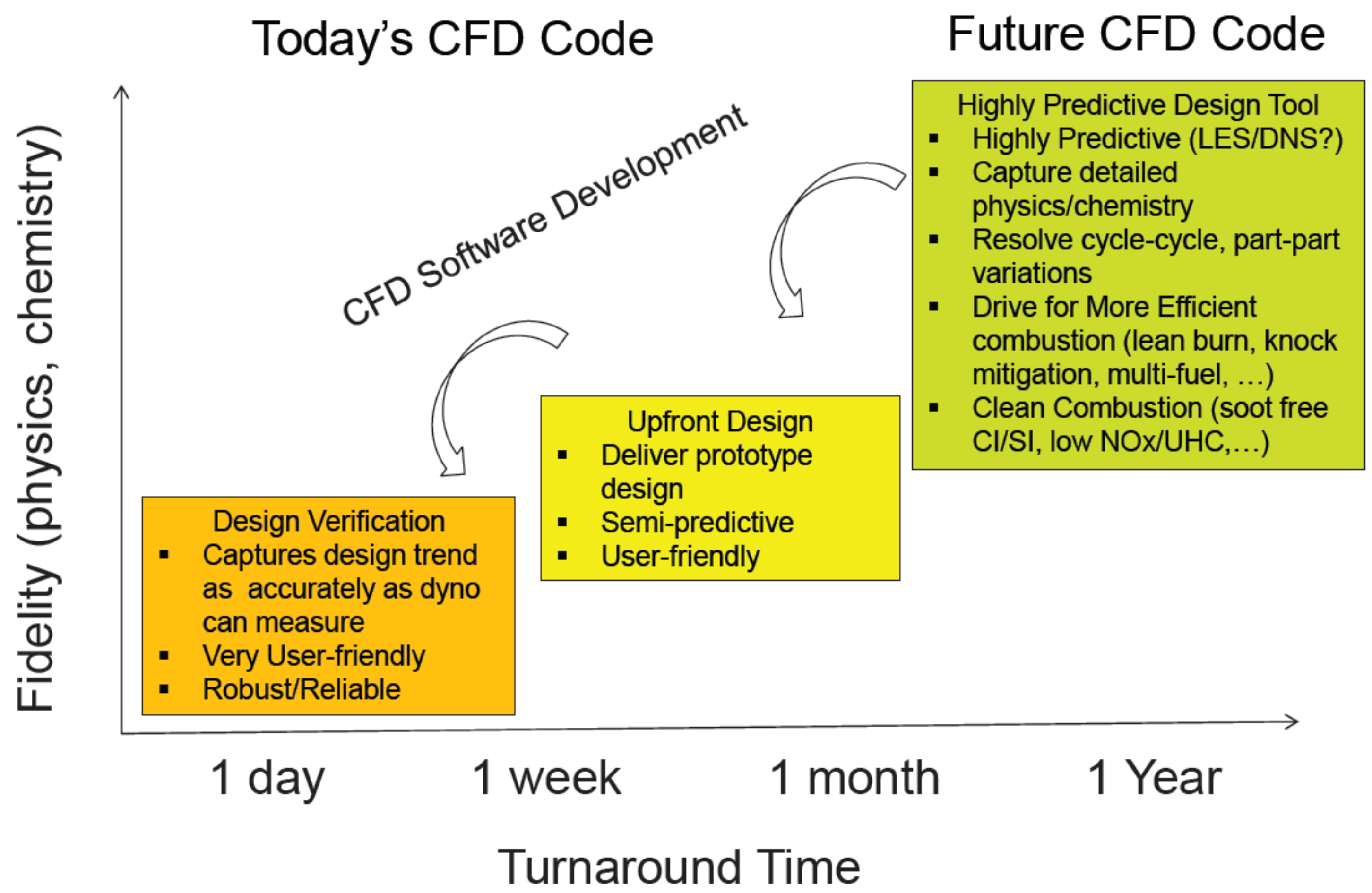


Fig. Rotating pre-chamber case

CFD软件的发展

CFD软件的发展


Today's CFD Code
Future CFD Code
CFD Software Development
Fidelity (physics, chemistry)
Design Verification
▪ Captures design trend as accurately as dyno can measure
▪ Very User-friendly
▪ Robust/Reliable
Upfront Design
▪ Deliver prototype design
▪ Semi-predictive
▪ User-friendly
Highly Predictive Design Tool
▪ Highly Predictive (LES/DNS?)
▪ Capture detailed physics/chemistry
▪ Resolve cycle-cycle, part-part variations
▪ Drive for More Efficient combustion (lean burn, knock mitigation, multi-fuel, …)
▪ Clean Combustion (soot free CI/SI, low NOx/UHC,…)
1 day
1 week
1 month
1 Year
Turnaround Time

感谢大家