

# ICSC 2017

CAE for virtual product

CAE for innovation

CAE for process transformation

IDAJ CAE Solution Conference

## CONVERGE 在内燃机燃烧学国家重点实验室 的应用现状

天津大学 内燃机燃烧学国家重点实验室

演讲人: 周磊 副教授



2017年11月15日

# Outline

- ✓ SKLE简介
- ✓ SKLE先进发动机燃烧技术研发平台
- ✓ IDAJ中国-SKLE基于CONVERGE的合作
- ✓ 基于CONVERGE的发动机燃烧过程研究案例
  - 1 内燃机重点实验室的部分工作
  - 2 二冲程船用柴油机喷雾燃烧系统开发
  - 3 二冲程双燃料发动机燃烧过程分析
- ✓ 总结和展望

# State Key Laboratory of Engines (SKLE) Tianjin University



■ 内燃机燃烧学国家重点实验室于1986年经国家计委批准开始建设，1989年建成并对外开放。是我国内燃机学科唯一的国家重点实验室。实验室以国家“能源、环境”发展战略为依据，以国家内燃动力工程的科技创新为导向，开展内燃动力工程中关键科学问题的基础理论研究、内燃动力工程新技术原理的创新研究和开展填补国家技术空白的集成创新研究。

■ 目前，实验室有教授19人、副教授17人、讲师3人、博士后4人，博士硕士共410人。

## 主要研究方向(内燃机)

- 内燃机燃烧过程及其优化控制
- 内燃机有害排放物的生成、对大气环境的影响及后处理
- 燃料与燃料燃烧基础理论
- 内燃机节能新技术与低碳动力装置
- 动力机械结构强度、振动、噪声及润滑技术
- 新能源技术

## 课题组研究方向

汽油机的早燃和爆震燃烧

汽油压燃发动机

低速二冲程船用发动机

先进的燃烧方式

先进的数值模拟方法

化学反应动力学

湍流燃烧

喷雾燃烧



### 自主开发模型与数值模拟工具

- 化学反应动力学高效计算程序包：ISAT/DAC/CA
- 标量小尺度混合模型程序包：LEM/ODT
- 一维可压缩，高精度计算程序包
- 三维LES/LEM并行计算程序
- 液体燃料喷雾燃烧程序

## 本人研究方向

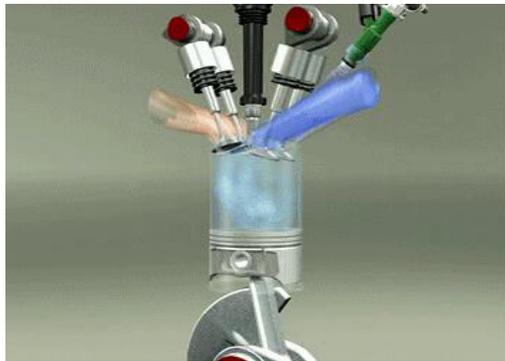
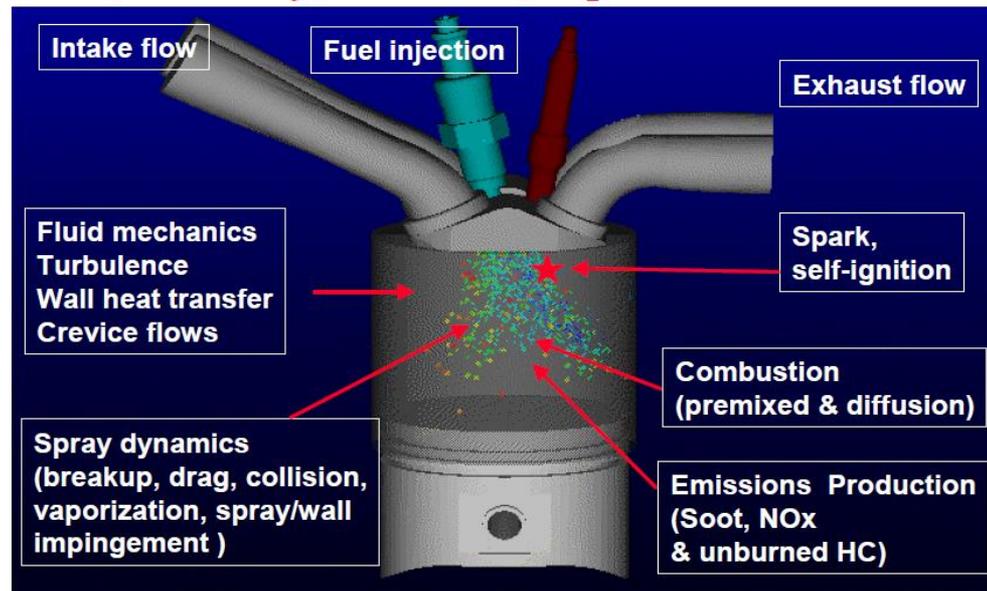
### 大涡模拟-spray and CCV

◆ CCV

◆ Spray

◆ Combustion

3-D, unsteady, turbulent, 2-phase reactive flow



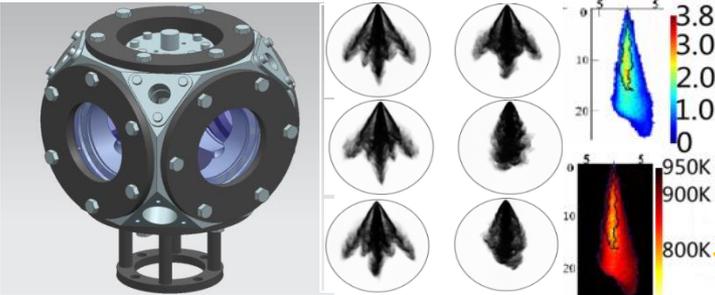
1. Combustion process simulations in ICE
2. Large eddy simulation (LES) for gasoline and diesel fuel spray
3. Combustion with detailed chemistry mechanisms (ISAT, DAC)
4. Multi-scale simulation coupling a Eulerian interface-tracking method and a Lagrangian particle tracking method
5. Turbulent combustion

# SKLE先进发动机燃烧技术研发平台

# R&D Platform @ State Key Laboratory of Engines

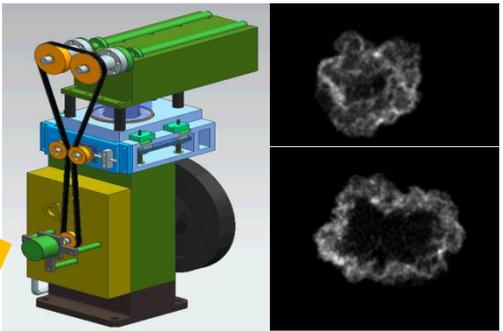
**Numerical Simulation + Optical Measurement** → Research of spray/combustion mechanisms  
**Single/Multi Cylinder Engine Experiment** → Development of combustion systems

## Spray and Laser diagnostics



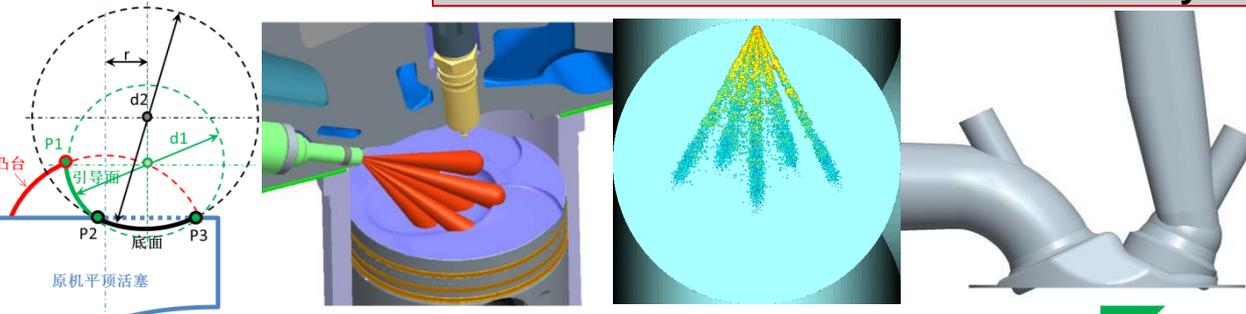
Atomization and breakup mechanisms

## Optical Engines



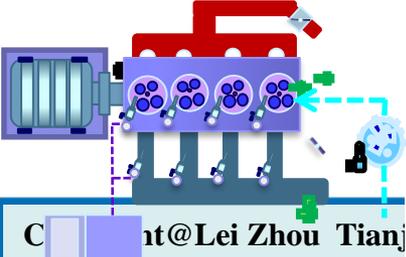
- 1 Evaporation
- 2 Stratification
- 3 Wall-wetting
- 4 Flow field analysis
- 5 Combustion

## Numerical simulation and combustion system optimization



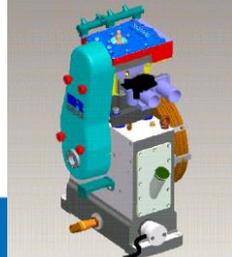
- 1 Spray and combustion models
- 2 Arrangement of fuel, flow and chamber
- 3 Optimization of intake systems and combustion chamber

## Multi-cylinder engine test



- 1 Performance test and parameter optimization
- 2 Practical application of combustion control strategies
- 3 Emission control

## Single-cylinder engine test



- 1 Performance and emission test
- 2 Combustion system design

# 重点实验室基于CONVERGE的发动机 燃烧过程研究案例

---

## 项目及发表论文

- ◆ **重点实验室使用Converge主要基于国家自然基金项目、国家自然基金重点项目、科技部重大专项、低速二冲程船机3个项目（使用量最大）、国家973项目、863项目等国家级项目**
- ◆ **发表论文：内燃机国际顶级会议SAE、Applied energy, Applied thermal engineering, energy and fuel, flow turbulence and combustion等国际SCI期刊**

## 研究背景

### ■ 内燃机：应用最为广泛的原动机

### ■ 内燃机在未来几十年仍将在移动式动力装置中占有支配地位。

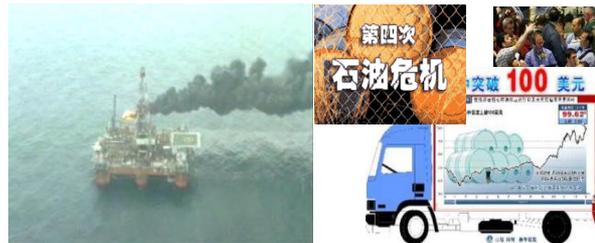
——美国科学院能源报告，日本跨部委战略创新项目，中国工程院论坛（2009-2013）

消耗石油**66%左右**  
原油对外依存度高(**60%**)

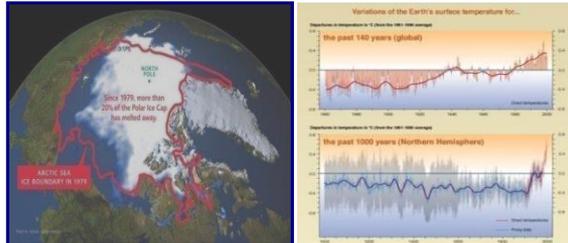
- CO<sub>2</sub>约占总排放的**25%**
- 越来越严格排放法规

- 主要污染源
- PM2.5、CH、NO<sub>x</sub>

#### 石油供应安全



#### 气候变暖

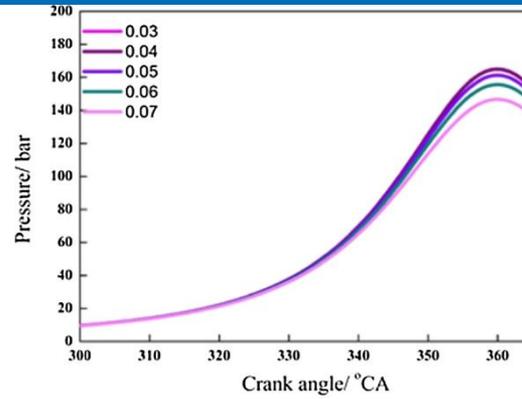
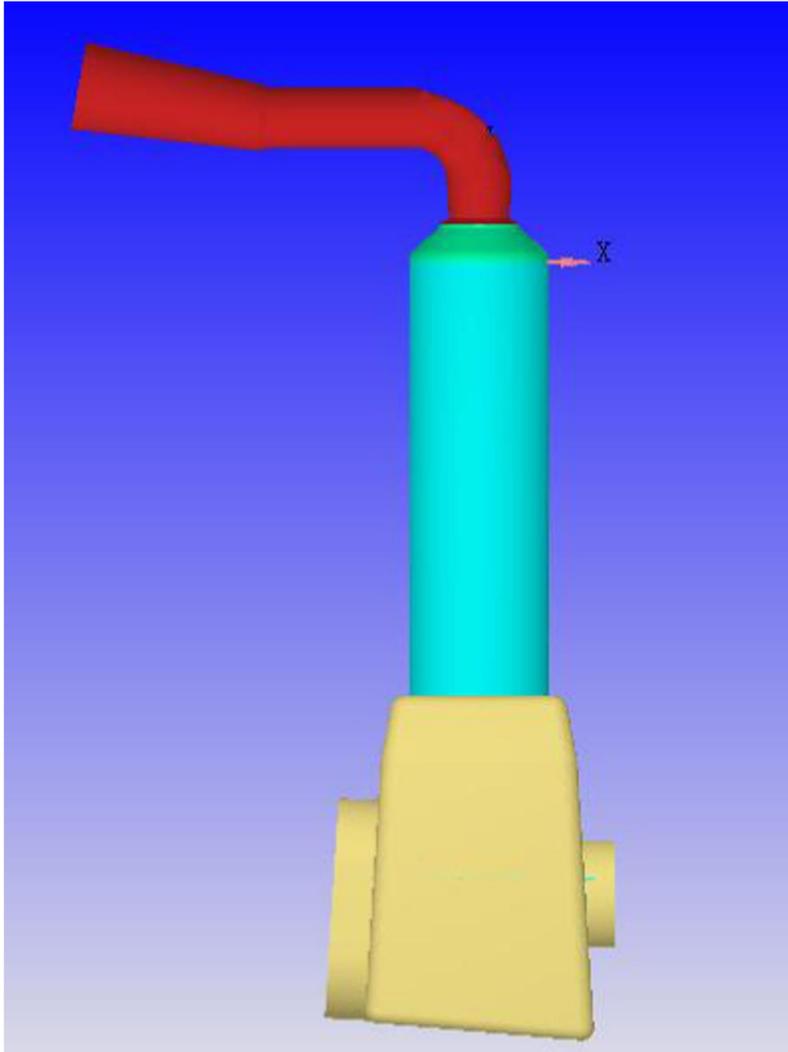


#### 环境污染

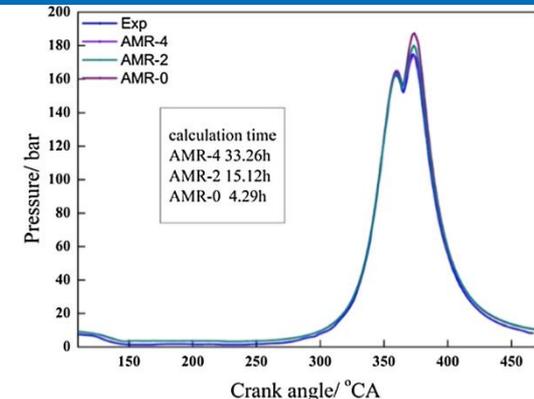


解决问题的核心：内燃机的高效（节能）清洁（减排）燃烧！

# 二冲程船机模拟



(a)



(b)

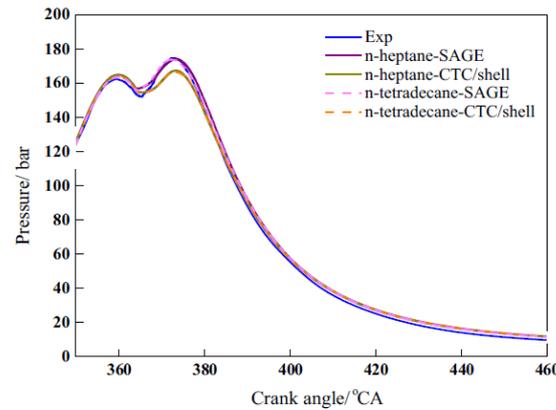


Fig. 5. The comparison of pressure for the different combustion models and alternative fuels.

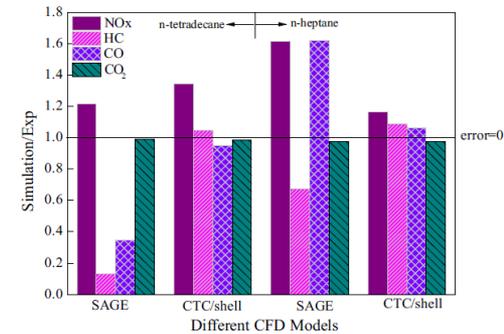
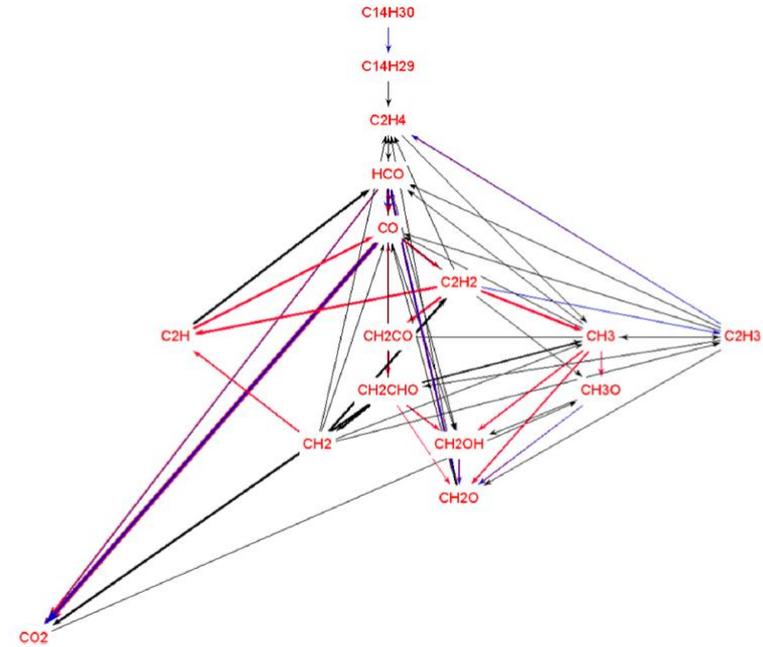
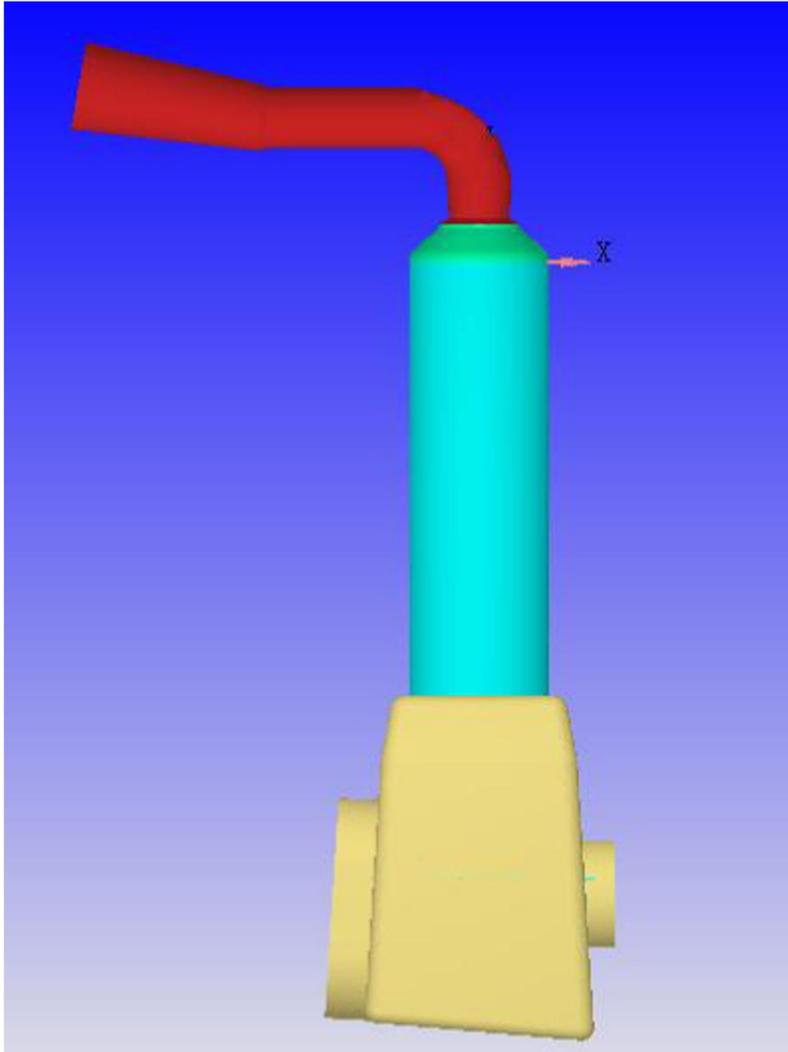


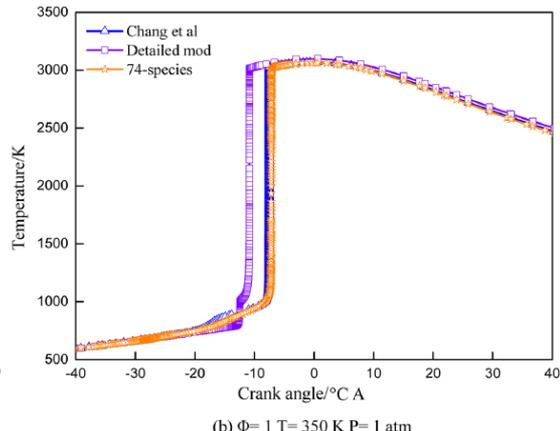
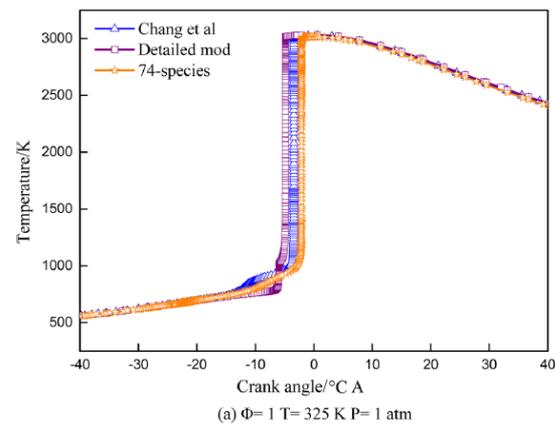
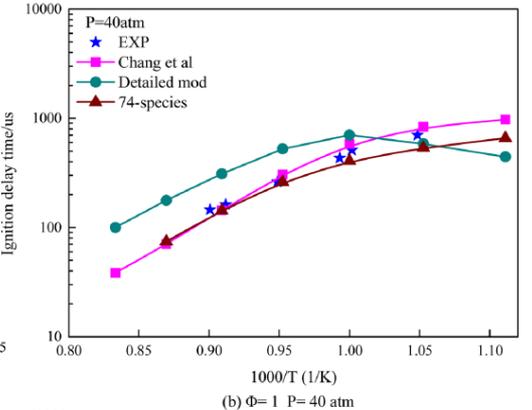
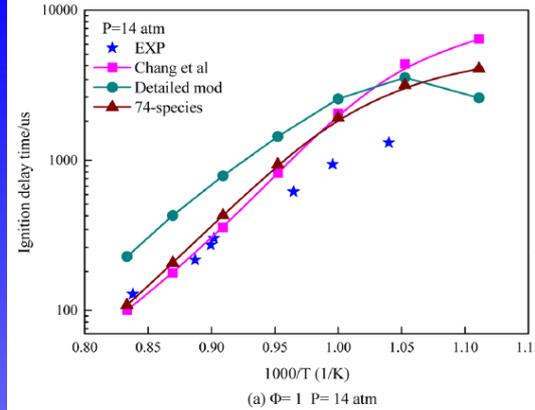
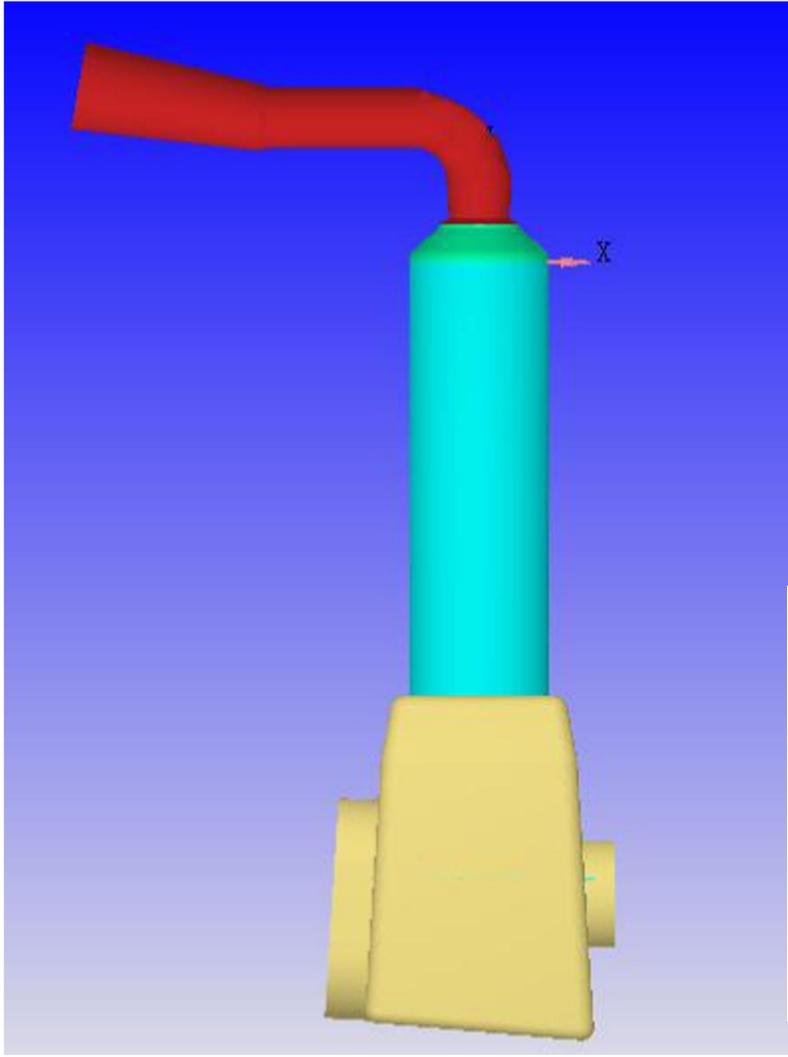
Fig. 8. The ratio of simulated and experiment measure for different combustion models and alternative fuels.

# 二冲程船机模拟



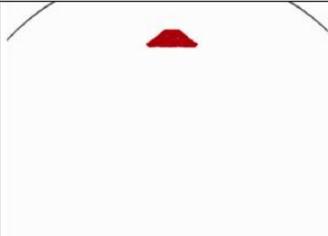
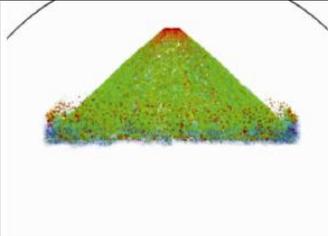
1. CO<sub>2</sub> reaction paths: the blue lines represent paths of HO<sub>2</sub> in the reaction; red lines represent paths of OH in the reaction.

# 二冲程船机模拟



# 二冲程汽油机油气混合

表 3 实验与仿真喷雾形态对比

时间	实验	仿真
喷油后 0.2 ms		
喷油后 0.7 ms		

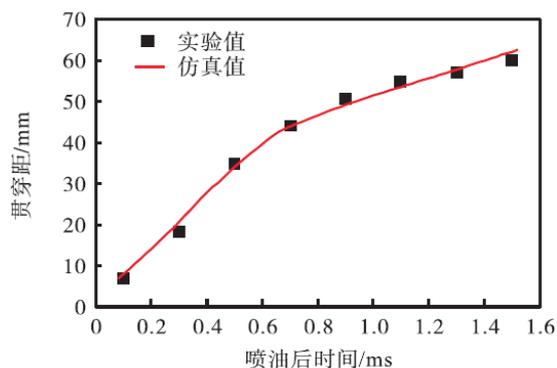


图 4 实验与仿真喷雾贯穿距对比

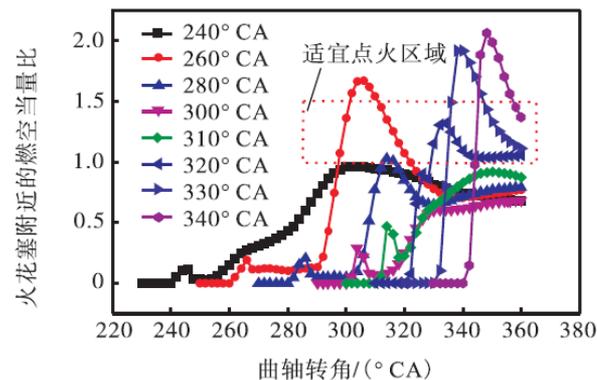
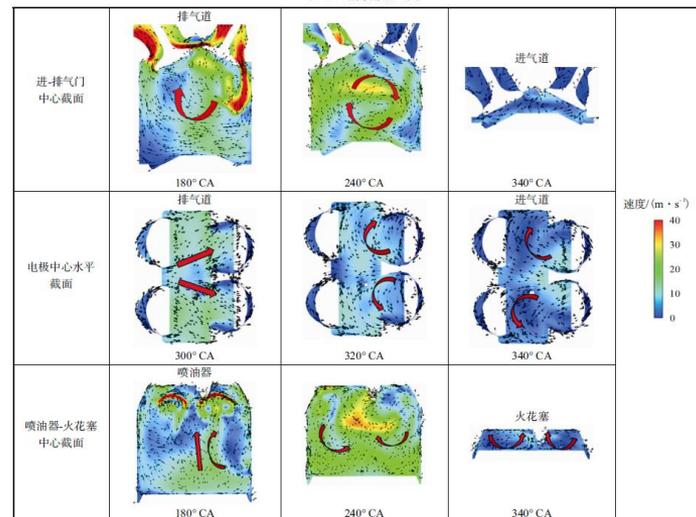


图 6 不同喷油时刻火花塞附近燃空当量比的变化历程

表 4 缸内流场云图



# 发动机Knock

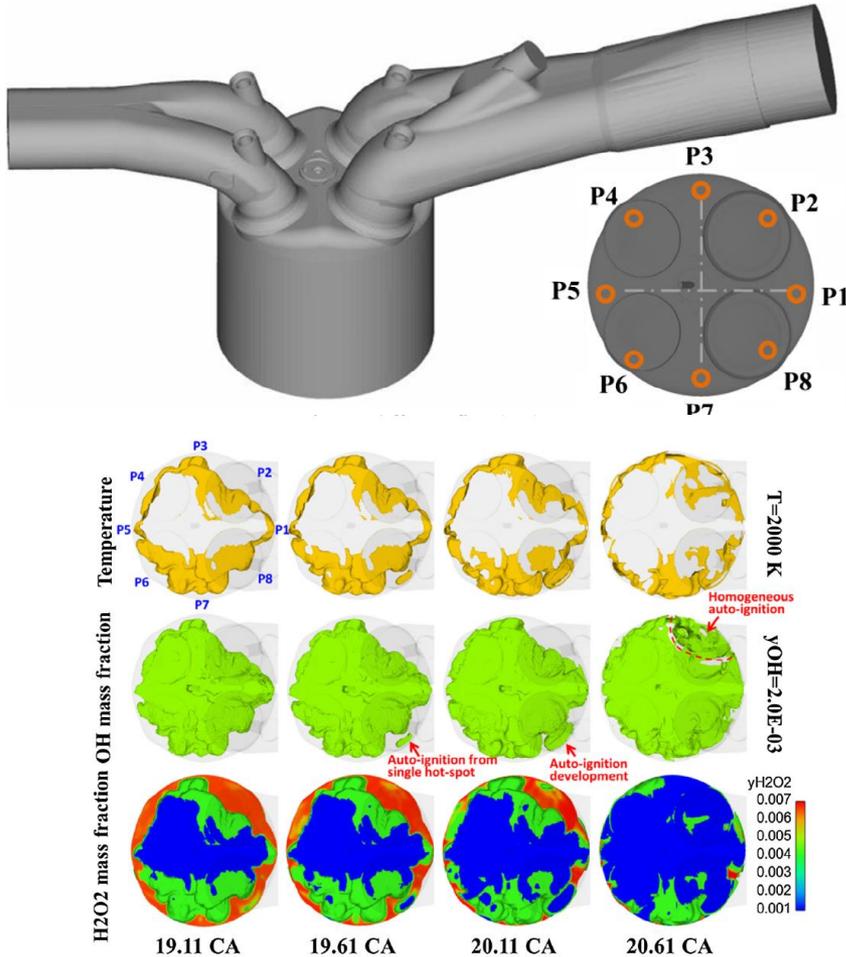


Fig. 5. Evolutions of flame propagation and end-gas auto-ignition at spark-ignition timing of ST = -8 CAD.

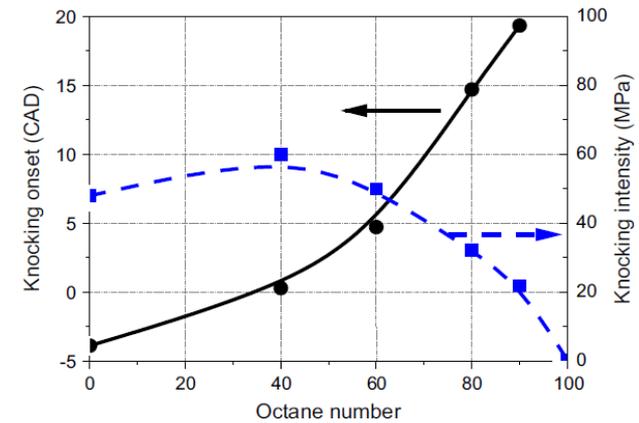
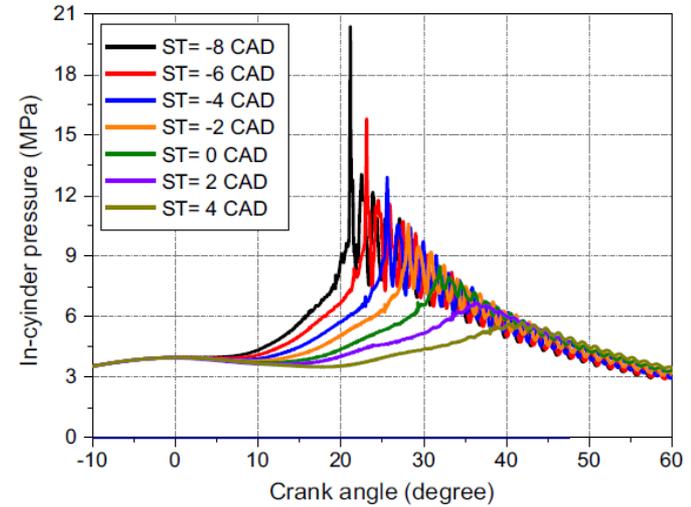
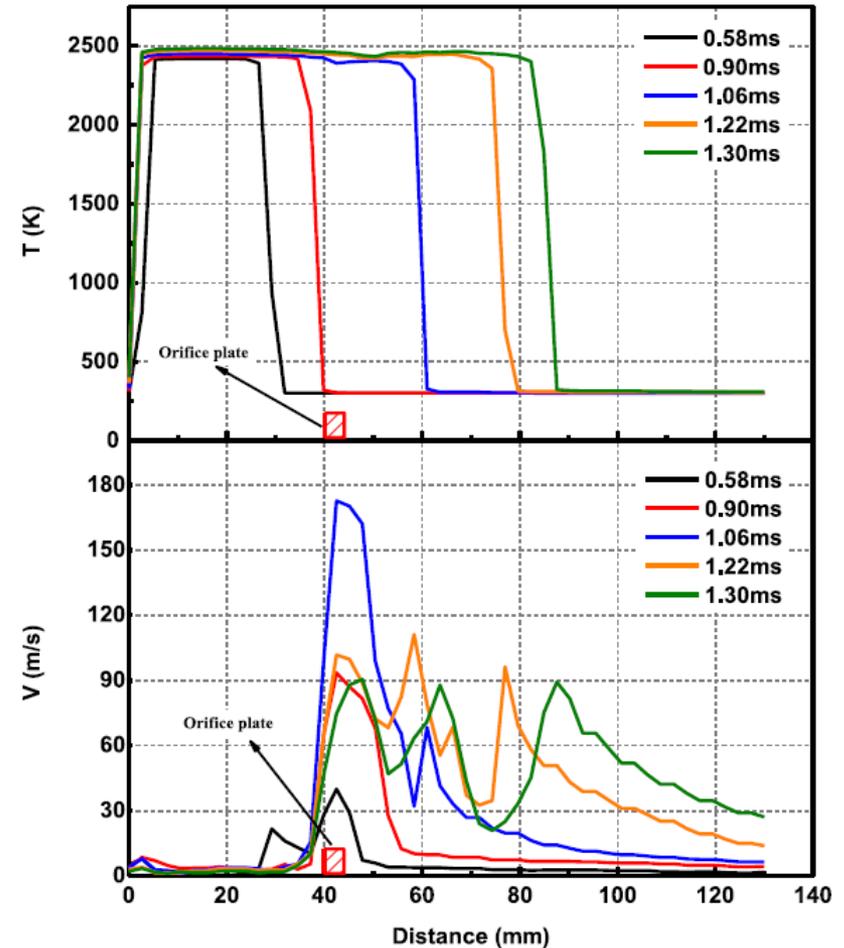
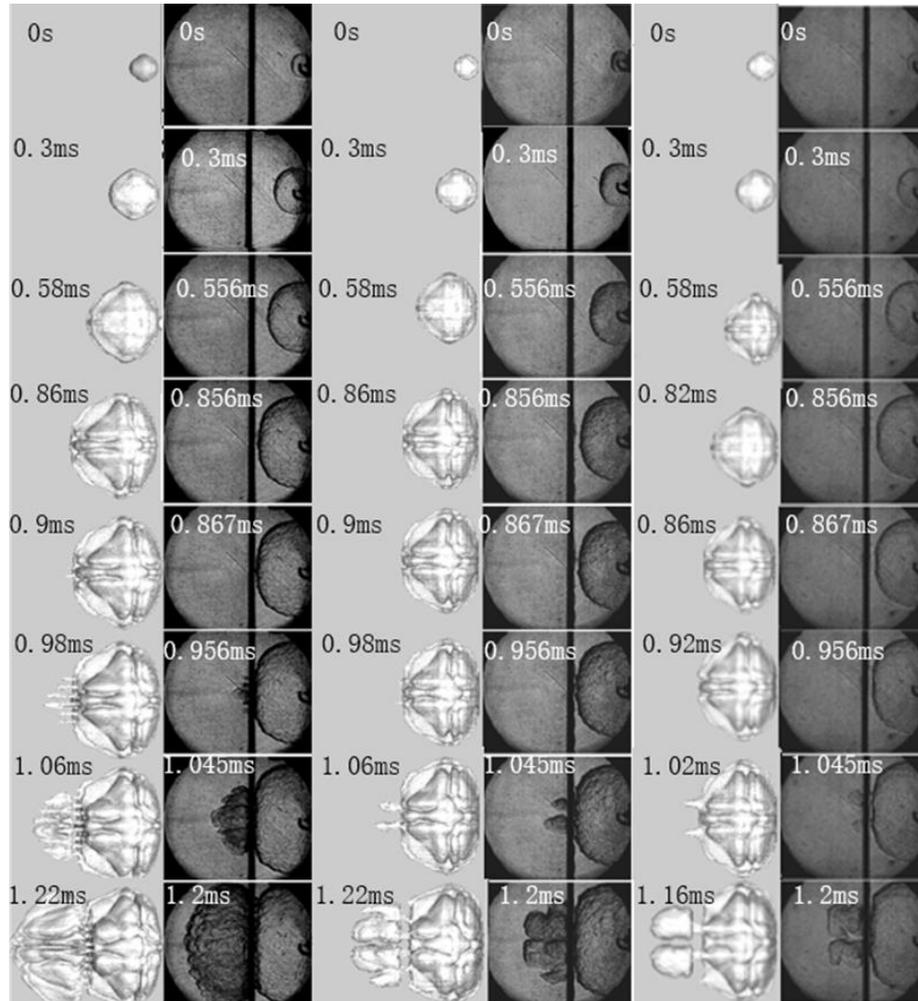


Fig. 7. Correlations between octane number and knocking onset and knocking intensity.

# 火焰加速机理



# NG燃烧过程

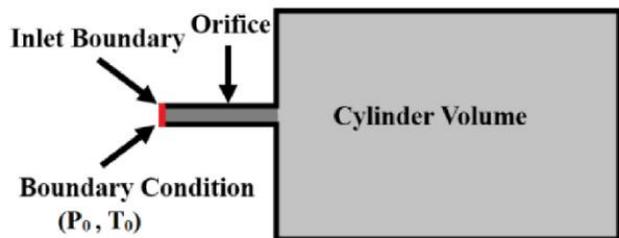


Figure 1. Diagram of gas injection model with one injector hole

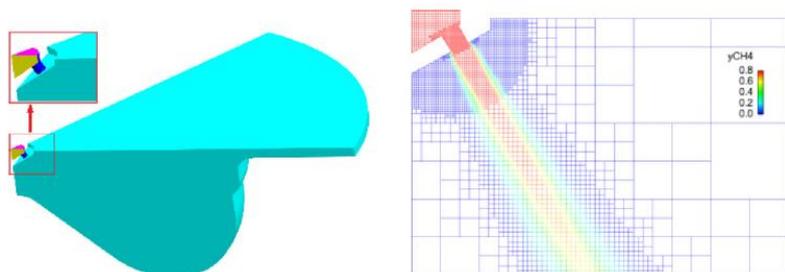


Figure 2. 1/6 engine sector domain and typical cell distribution in the NG injection process

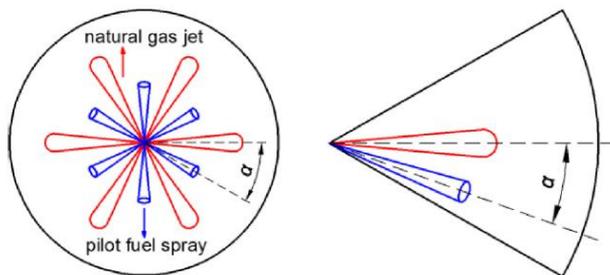


Figure 10. Injection directions of Natural gas jet and diesel spray

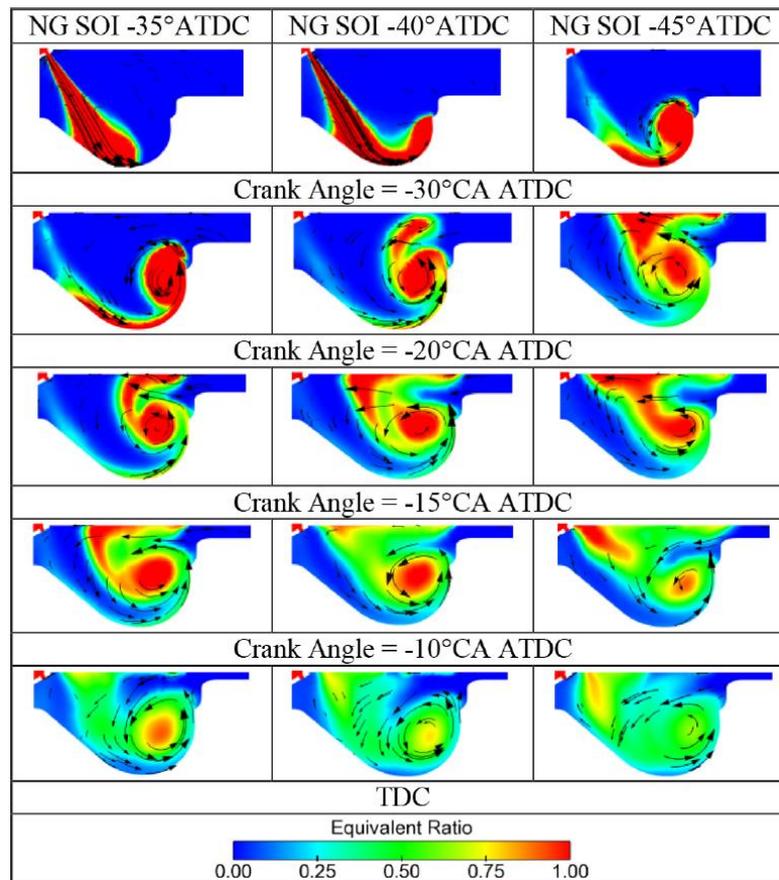


Figure 12. Equivalent ratio and velocity distributions of NG/Air in the mixing process (only cut-plane O-O is used)

# 二冲程船用柴油机扫气系统开发

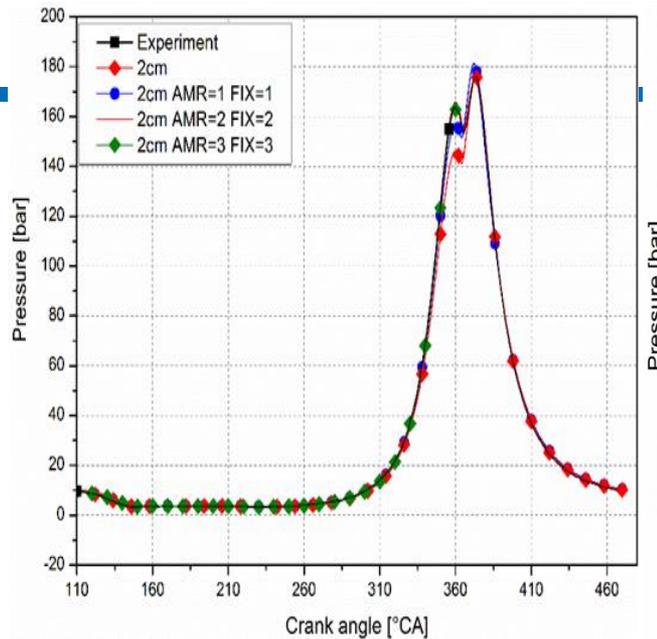
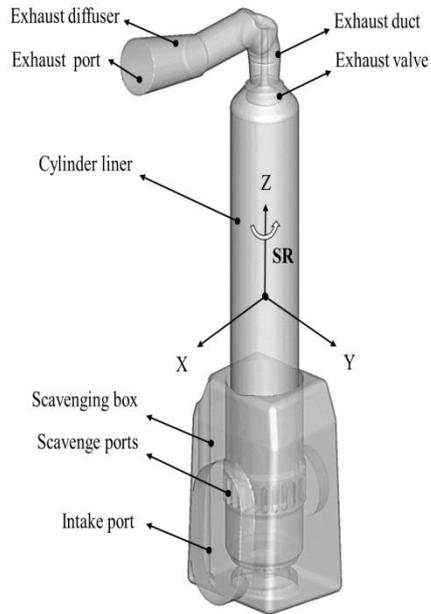


Figure 1. Mesh sensitivity analysis

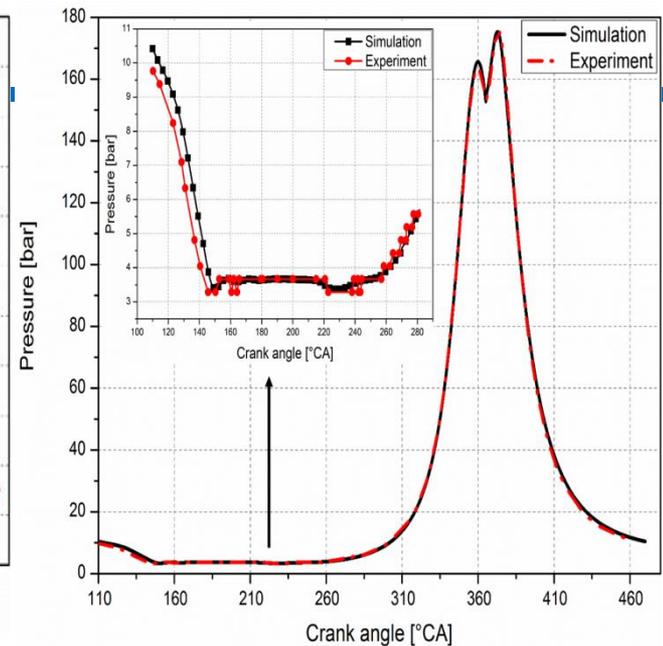


Figure 2. Cylinder pressure of simulation and experiment (20mm basic cell size with AMR=2 FIX=2)

The simulation are performed by Converge version 2.3. The turbulence model is RNG k- $\epsilon$  with PISO algorithm. The computing resource is TH-1A supercomputer system with 8 nodes of 96 cores.

As the Fig.1 shows, the results show that there is not much difference from 110° CA to 300° CA. The main difference is embodied in compression pressure at TDC. Two mesh strategies (20mm basic cell size with AMR=2 FIX=2, 20 mm basic cell size with AMR=3 and FIX=3) are in good agreement with experiment data.

As the Fig.2 shows, under the condition of 20mm with AMR=2 and FIX=2, the simulation results are already in good agreement with the experiment.

Bore	350 mm
Stroke	1550 mm
Connecting rod	1550 mm
Compression ratio	21:1
Cylinders	6
Exhaust Valve Open (EVO)	117° CA @ 45 mm lift
Exhaust Valve Close (EVC)	275° CA @ 45 mm lift
Scavenge Ports Open/Close (SPO/SPC)	145° CA /215° CA
Max engine speed	142 rpm

# 二冲程船用柴油机扫气系统开发

By adjusting the swirl orientation angle(SOA) from  $SOA=10^\circ$  to  $SOA=30^\circ$ , different swirl ratios are generated and have obvious difference in flow characteristics. The scavenging efficiency, retaining and charging efficiency are also improved with a larger SOA.

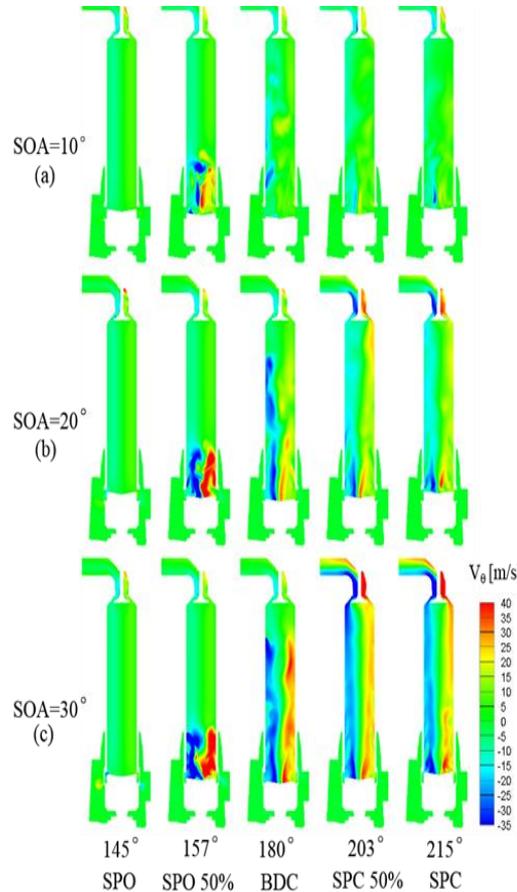
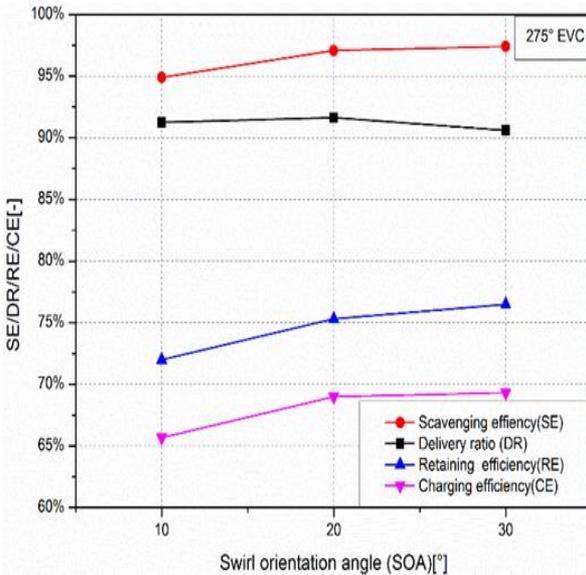
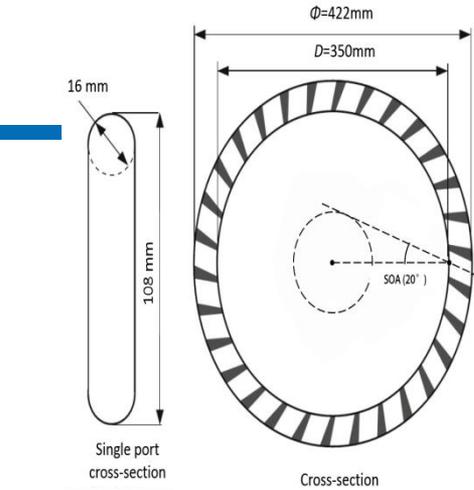


Figure 4. In-cylinder distribution of tangential velocity.

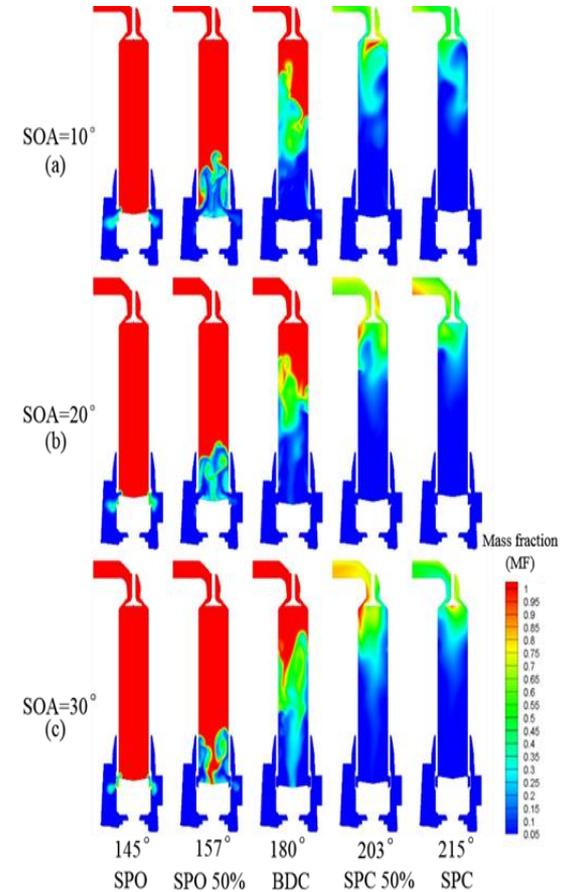
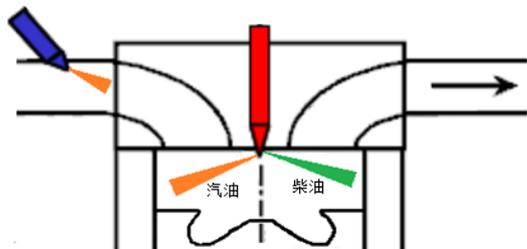


Figure 5. In-cylinder distribution of exhaust gas

## 仿真研究方案

### ■ RCCI燃烧机理的研究



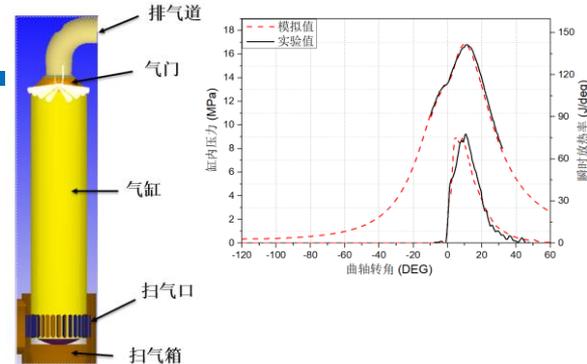
- 将部分气道预混汽油采用缸内直喷的方式引入气缸以提高缸内的浓度分层的燃油喷射策略，对燃油预混比例、汽油喷射时刻、柴油喷射时刻、柴油循环油量四个参数进行优化

### ■ GCI的喷雾燃烧仿真研究

物理过程	模型
湍流	LES /RANS
喷雾	Blob
破碎	KH-RT
蒸发	Frossling
碰撞	O'Rourke
液滴拖曳	Dynamic drop drag
化学机理	PRF简化机理
NO <sub>x</sub> 模型	Zeldovich
碳烟模型	Hiroyasu/NSC

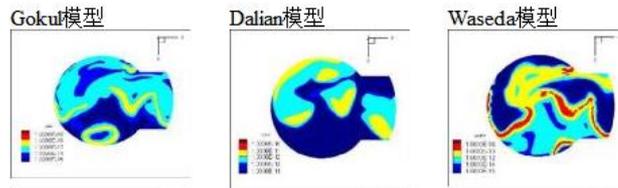
- 采用LES与RANS计算单次喷射的GCI，观察三维云图的差异性。

### ■ 船用双燃料的仿真研究



- 基于某船机模型计算了喷油策略、EGR、燃烧室结构参数等对于燃烧过程及排放结果的影响。

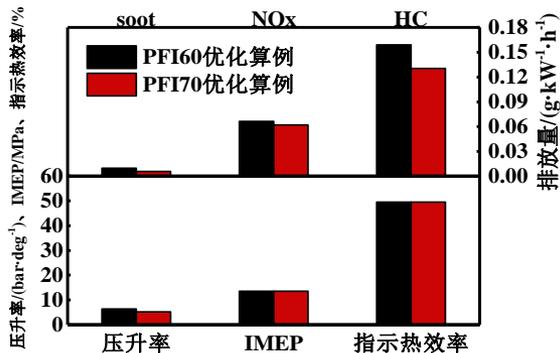
### ■ GCI燃烧碳烟生成历程的研



- 基于光学诊断结果比对了三种碳烟模型对GCI燃烧碳烟生成的预测差异。

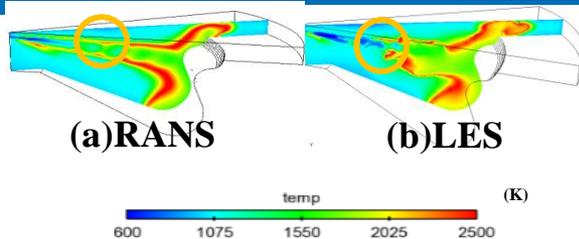
## 研究结果

## ■ RCCI燃烧机理的研究



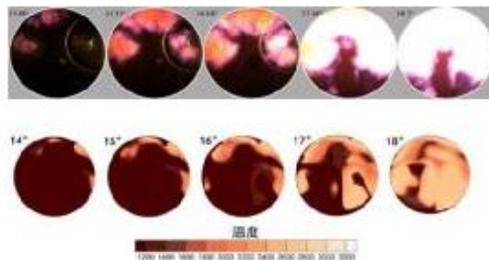
- 汽油采用进气道+缸内直喷的混合喷射策略可以增强缸内的混合气浓度分层
- 该喷油策略得到的优化结果相比于基准工况在IMEP保证不变的前提下，压升率和NOx分别降低了41%和46%，soot略有升高。

## ■ GCI的喷雾燃烧仿真研究



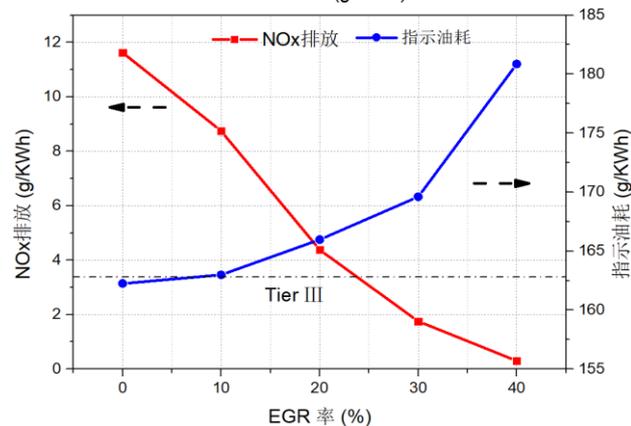
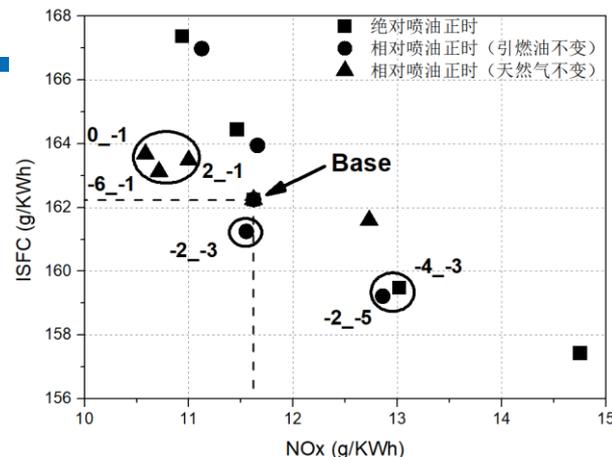
- 采用LES计算GCI后着火时刻与燃烧过程的计算更准确。

## ■ GCI燃烧碳烟生成历程的研究



- Gokul的碳烟模型在一定程度上与光学诊断结果最为接近。

## ■ 船用双燃料的仿真研究



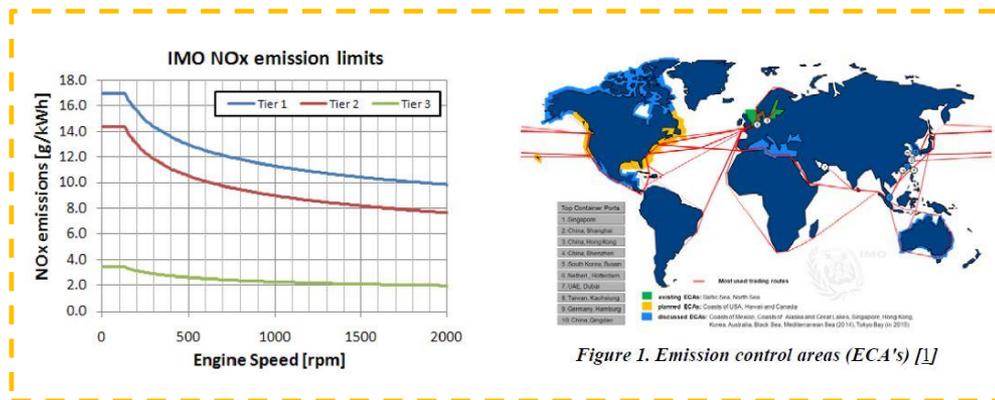
- 应用喷油正时耦合EGR策略对船机双燃料的燃烧和排放做了优化研究。

# 基于CONVERGE的船机燃烧过程研究案例

# 背景介绍

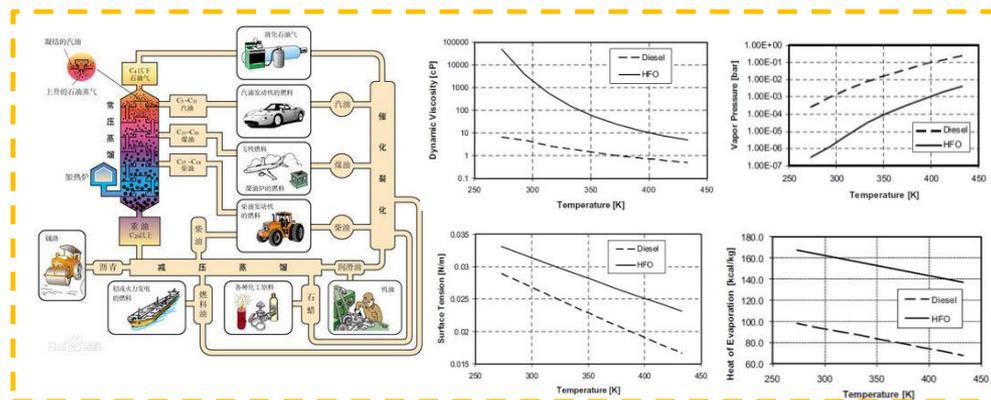
## 节能减排

国际海事组织IMO制定的排放法规日益严格  
重要衡量指标—氮氧化物



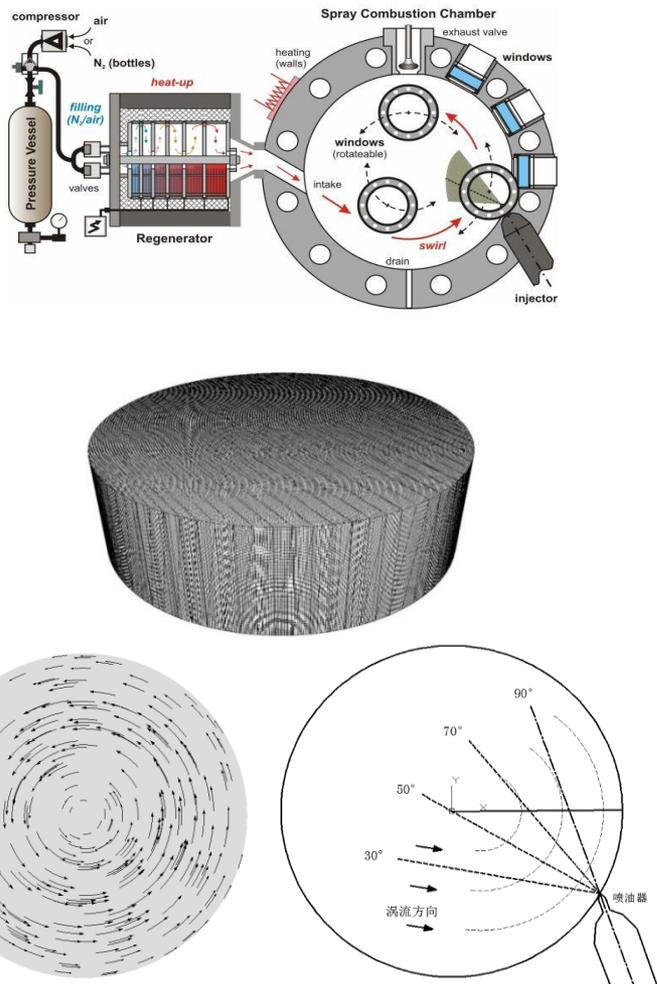
## 船机燃油

重油为主  
储量巨大,价格低;组分复杂,缺少深入研究  
柴油为辅(近海岸)  
排放效果好;成本高  
低速二冲程船机实验成本高,采用CFD模拟精度相对较高且成本低



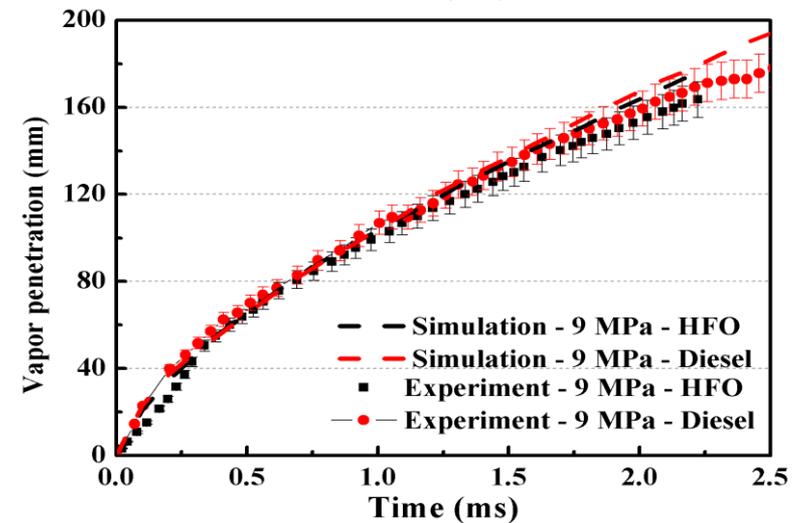
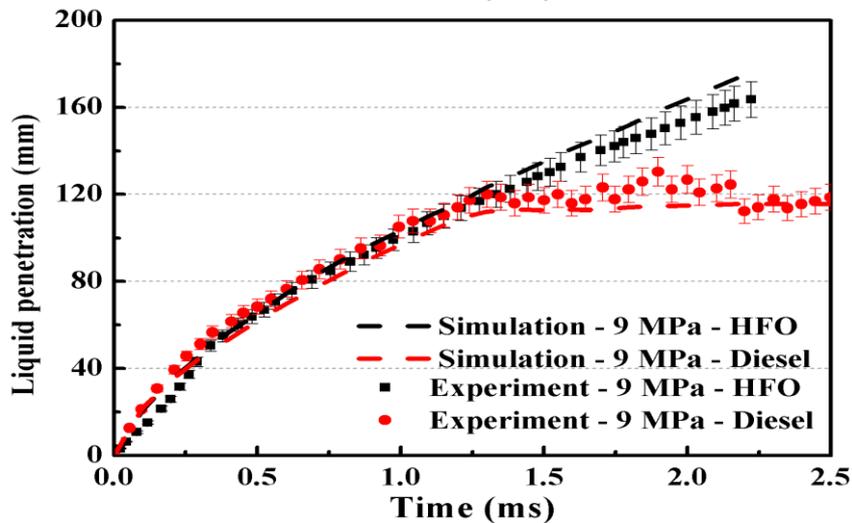
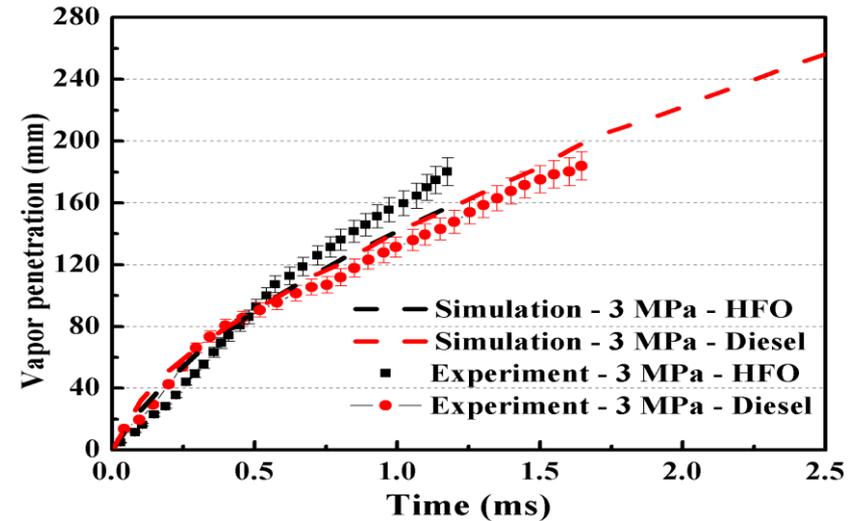
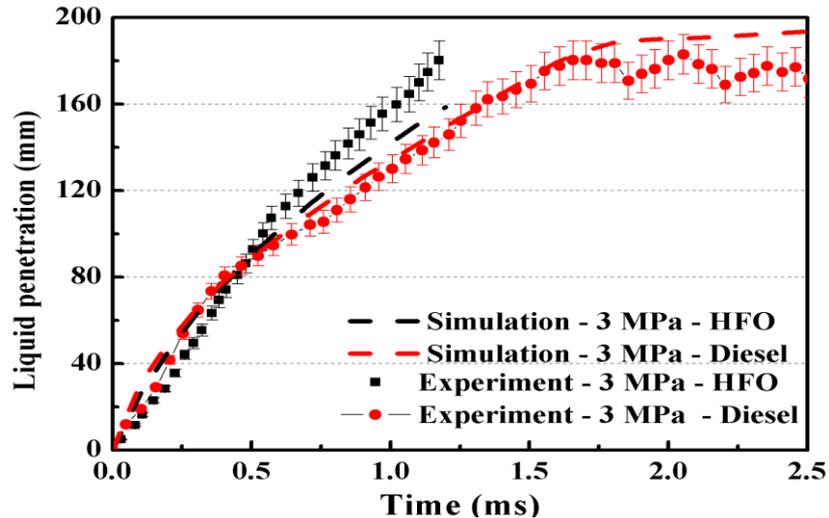
# 定容弹中冷态喷雾的研究

## 计算条件

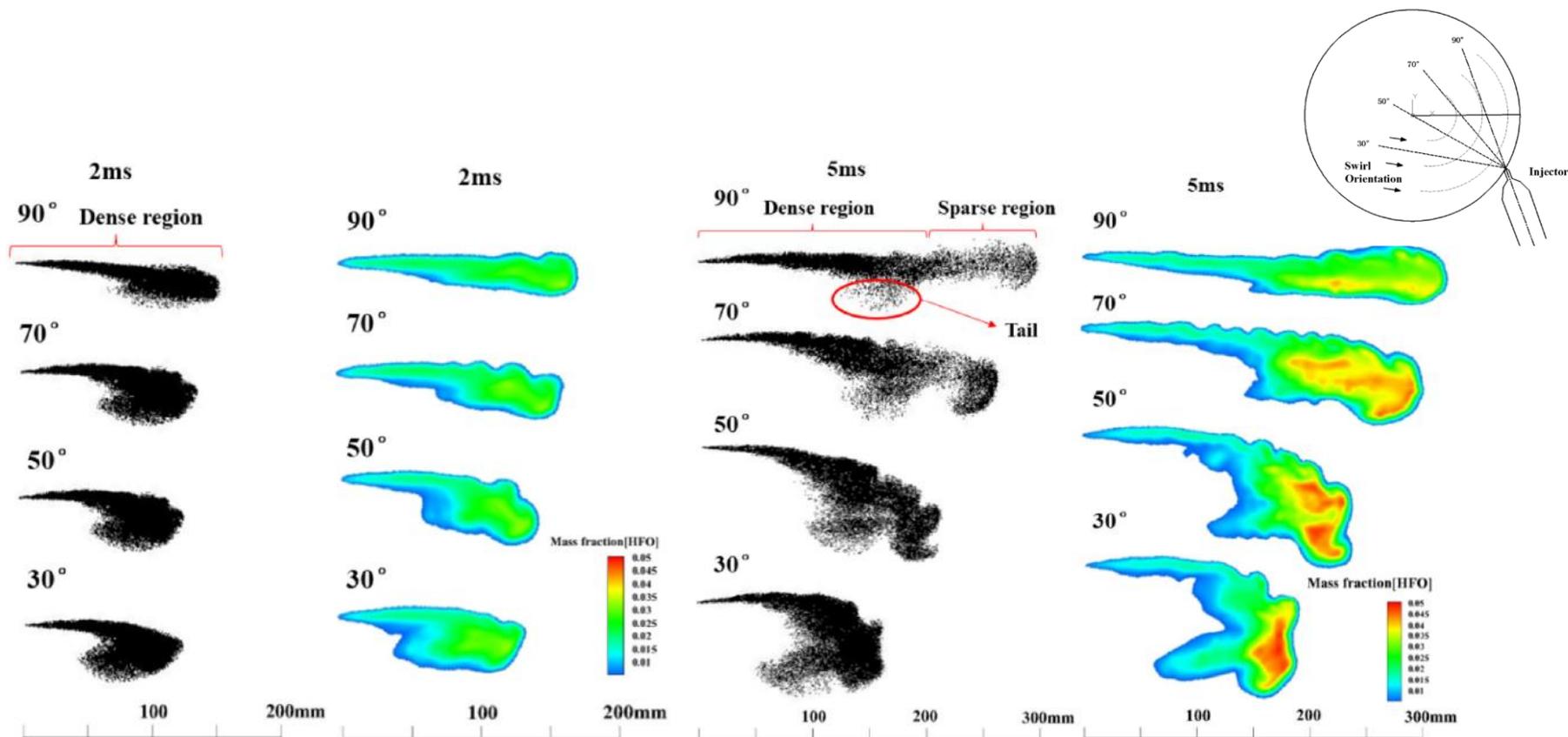


边界条件	旋流式定容弹
直径(mm)	500
高(mm)	150
环境气体压力(bar)	90/60/30
环境气体温度(K)	900
喷油压力(bar)	1000
喷油持续期(ms)	25
喷孔直径(mm)	0.875
燃油温度(K)	400
涡流速度(m/s)	15~25
环境气体	N <sub>2</sub>

# 燃油性质对喷雾的影响



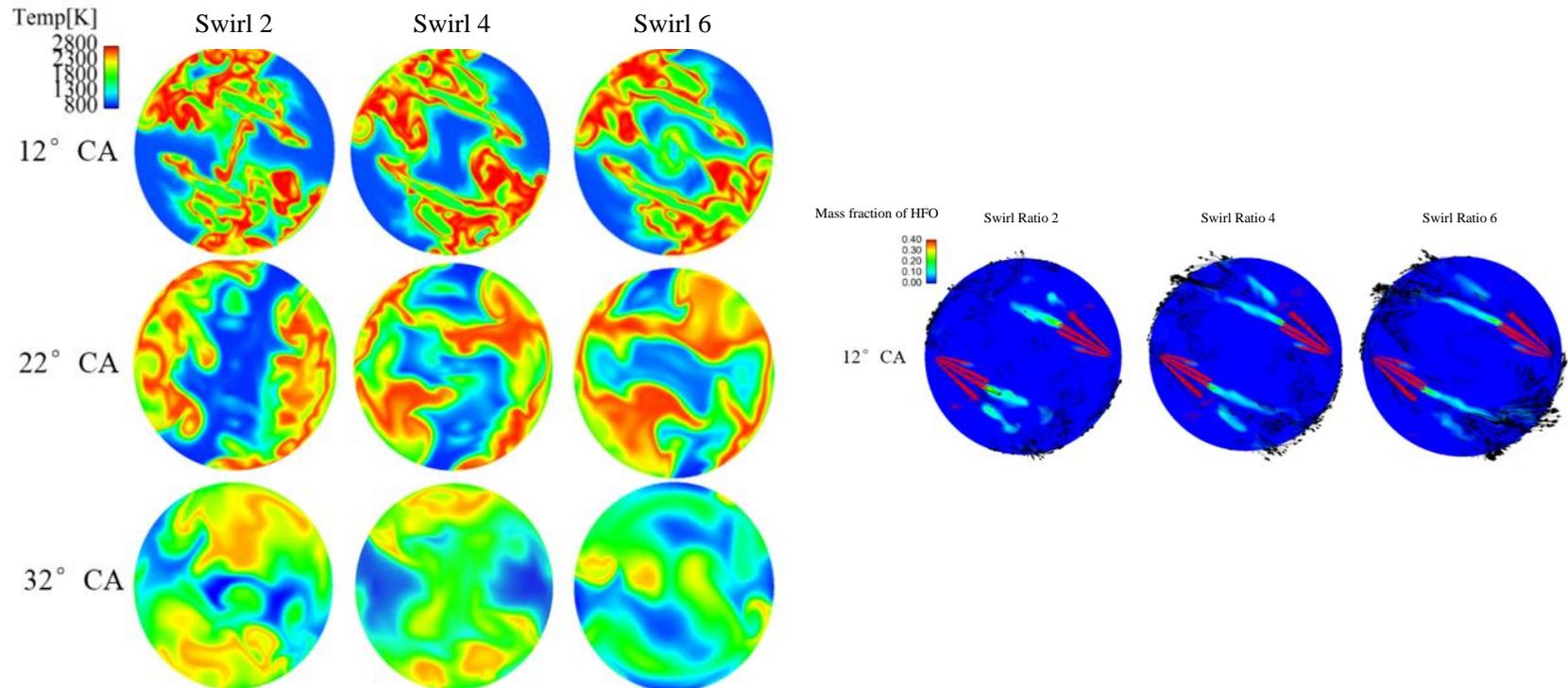
# 气流运动对重油喷雾的影响



b) Evolutions of spray configuration

Fig. 4. Comparison of the spray configuration under different spray orientations.

# 涡流比对船用柴油机燃烧和排放的影响



# 燃烧模型对船用柴油机燃烧和排放的影响

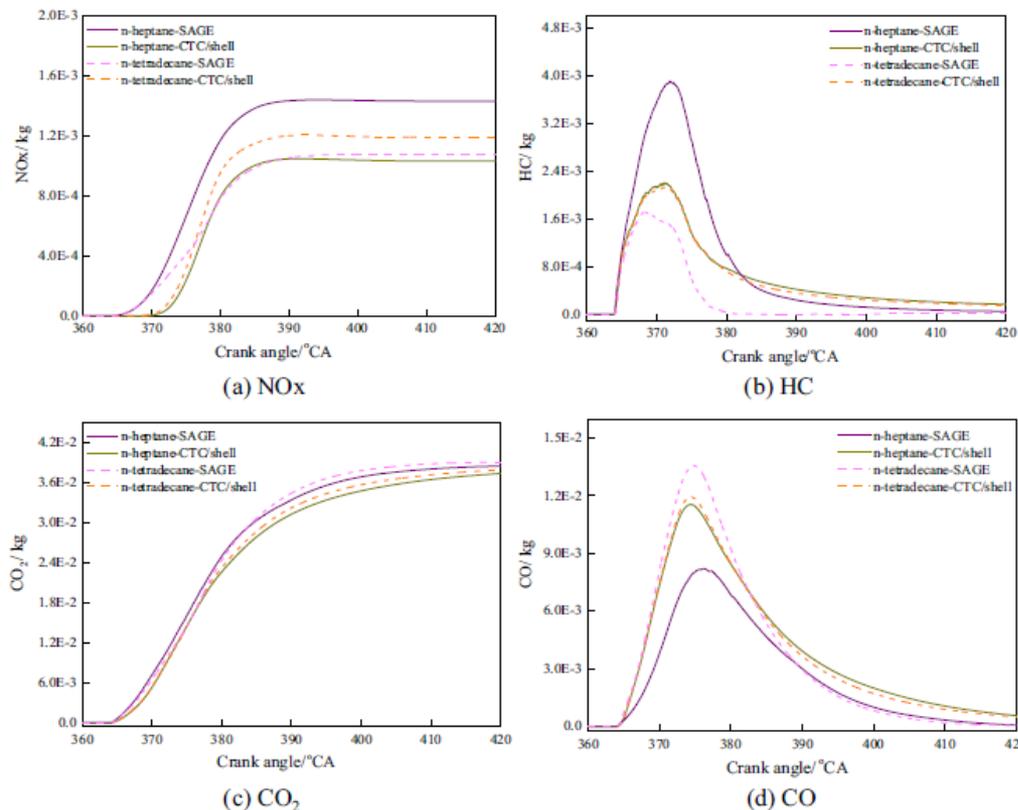
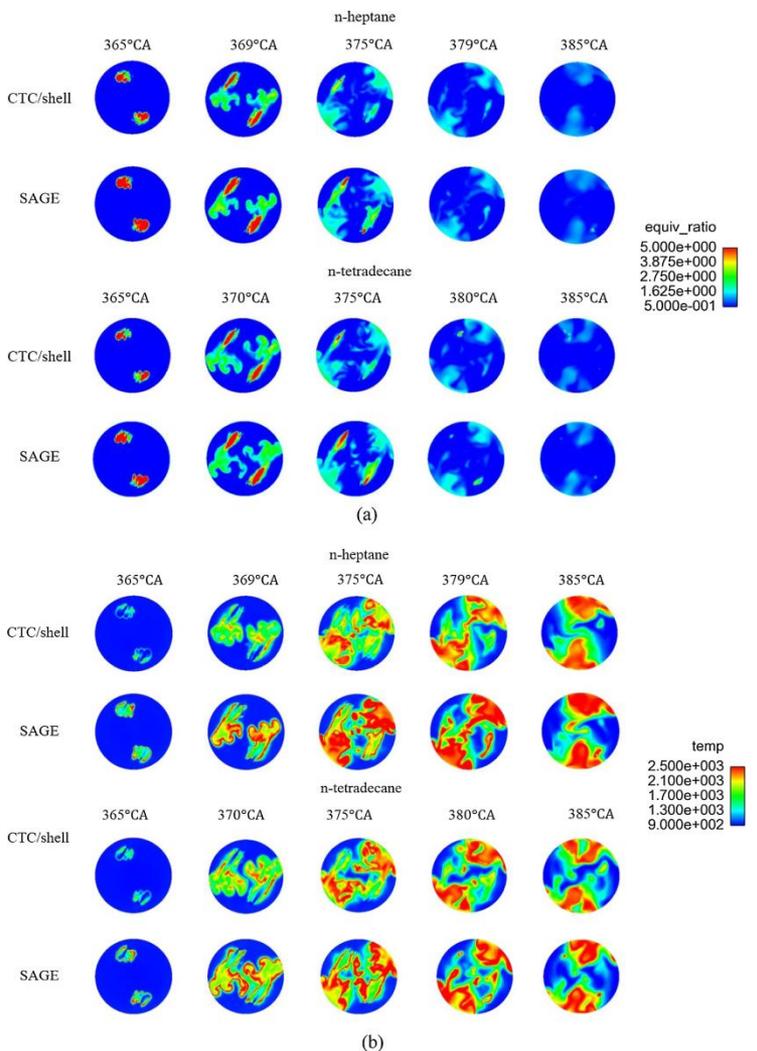
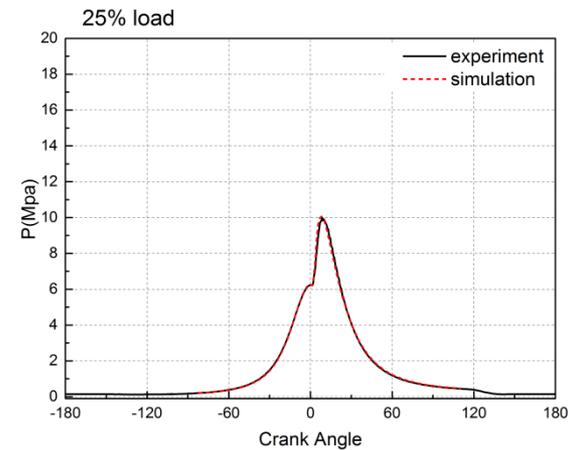
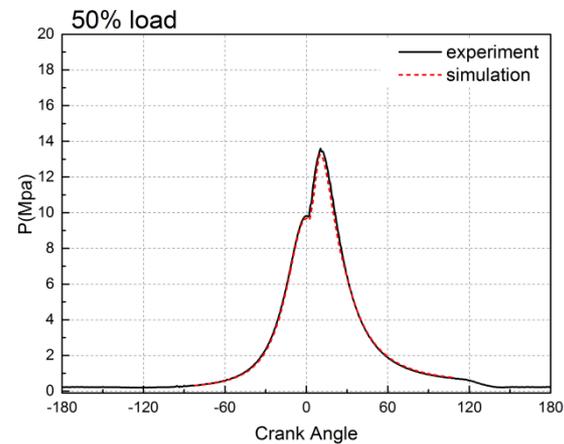
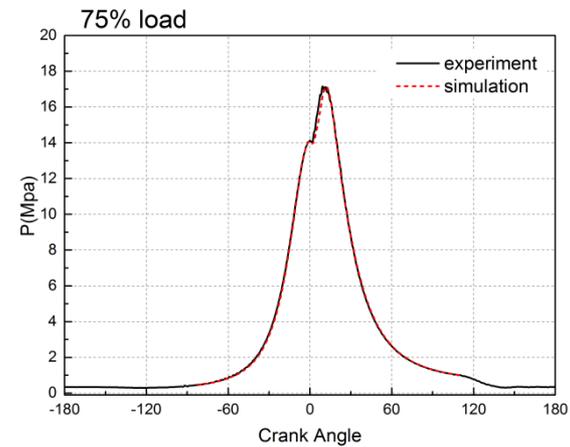
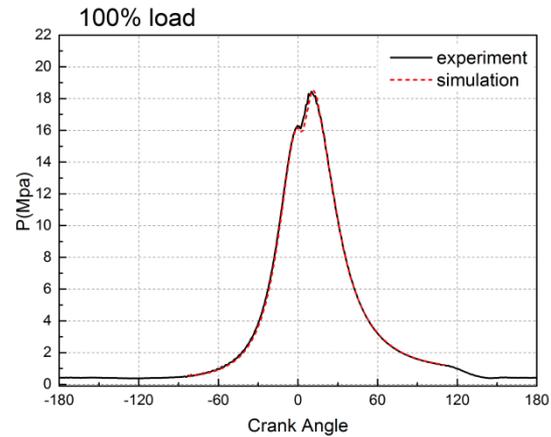
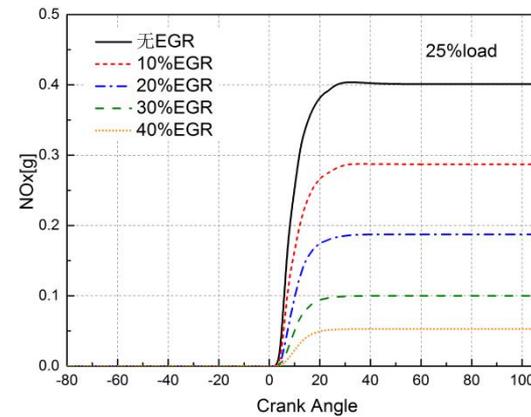
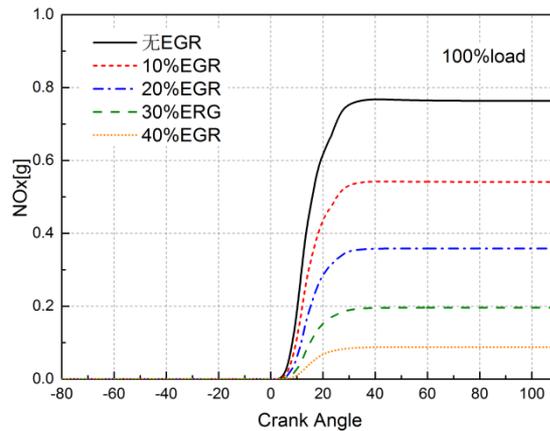
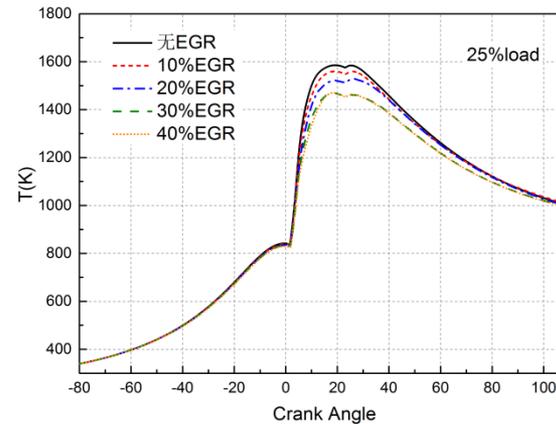
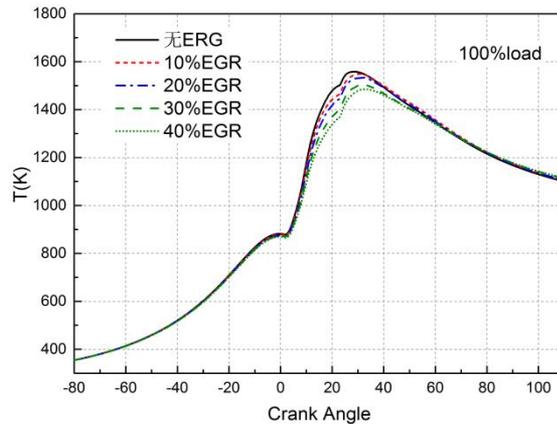


Fig. 9. The comparisons of emission mass for model: (a) NOx (b) HC (c) CO<sub>2</sub> and (d) CO.

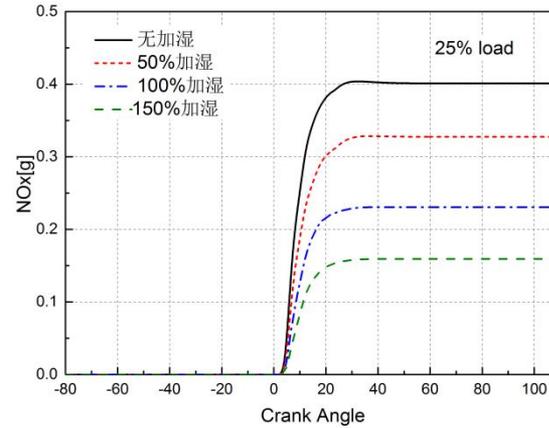
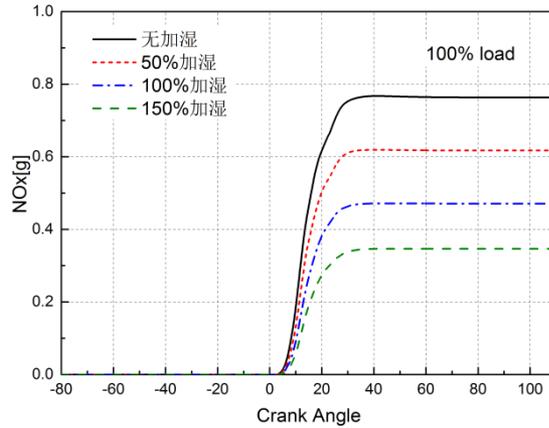
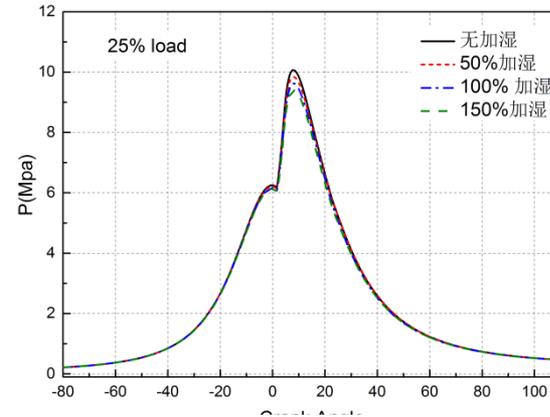
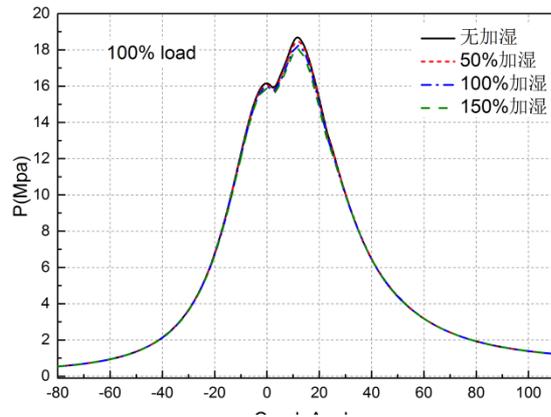
# 降低污染物措施



# 降低污染物措施



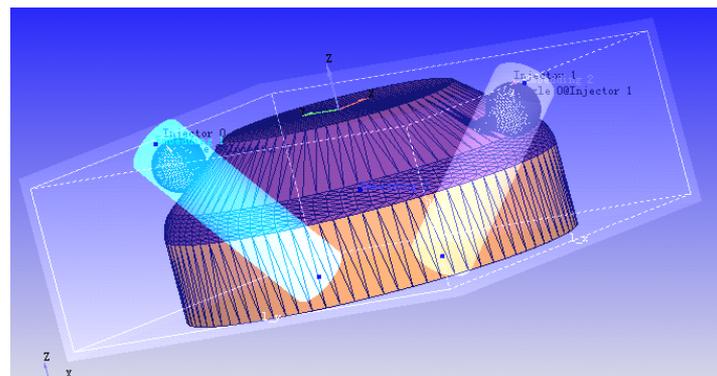
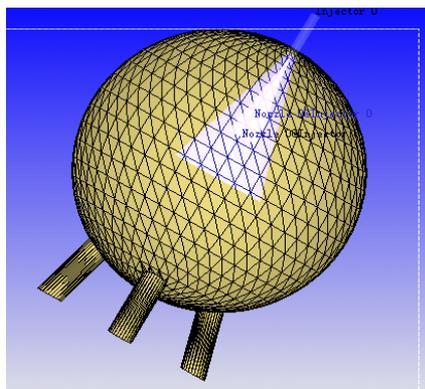
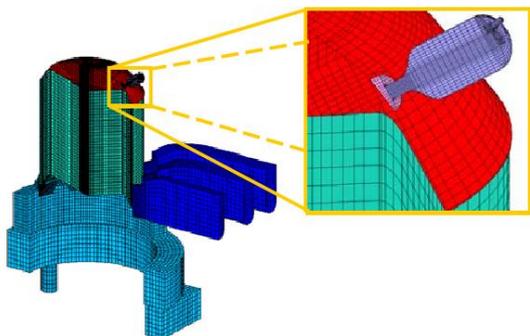
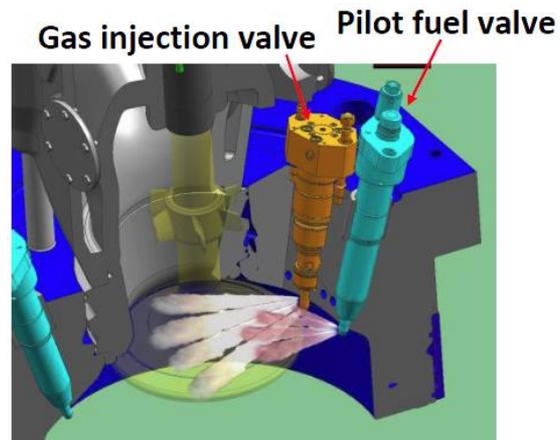
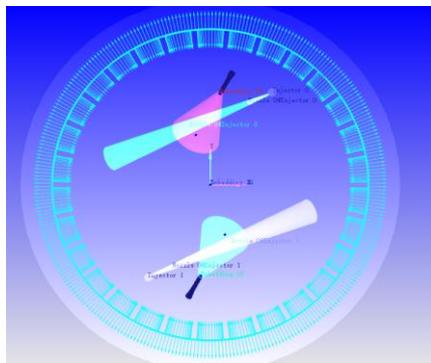
# 降低污染物措施



# 基于CONVERGE双燃料发动机研究案例

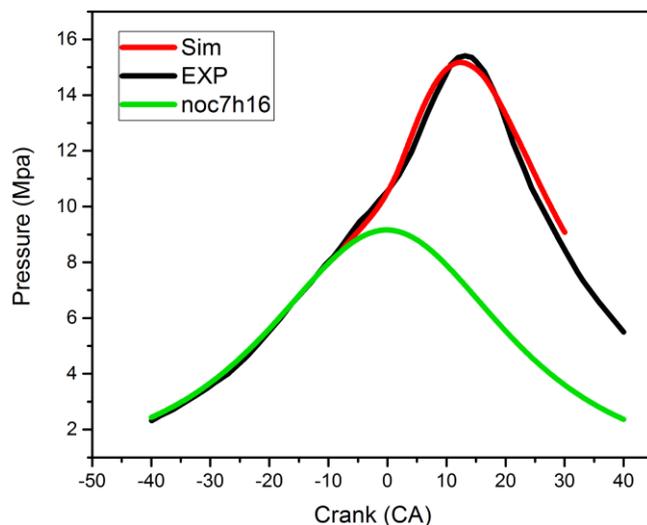
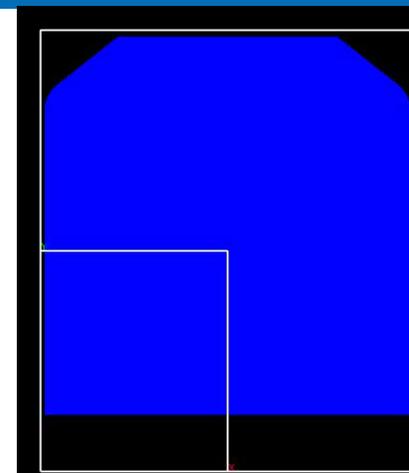
---

## 二冲程双燃料船机模拟

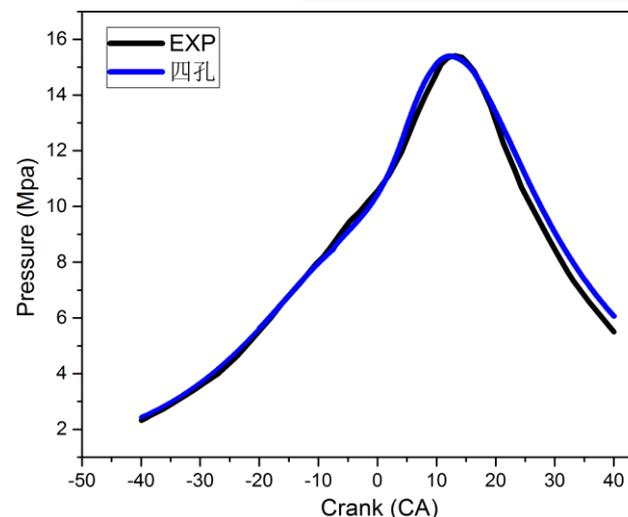


- 上面是高压，根据MAN公司4T50ME-GI的500缸径的建模
- 下面是低压，根据瓦锡兰RT-flex50DF的500缸径的建模

缸径冲程/mm	500 × 2050	SOI/deg	-10
转速/rpm	117	喷油量/mg	100 × 2
有效压缩比	10	喷油压力 /bar	36Mpa
压缩比	12	甲烷量/g	30
初始温度/K	580	引燃油比例	0.667%
初始压力/Pa	2435570	当量比	0.38

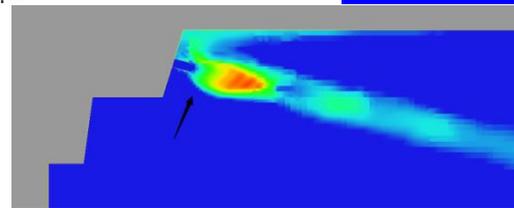
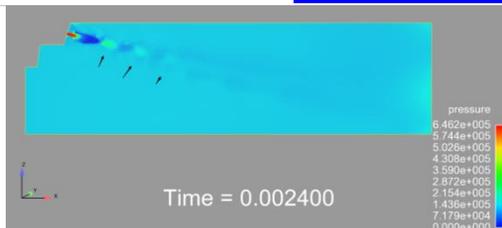
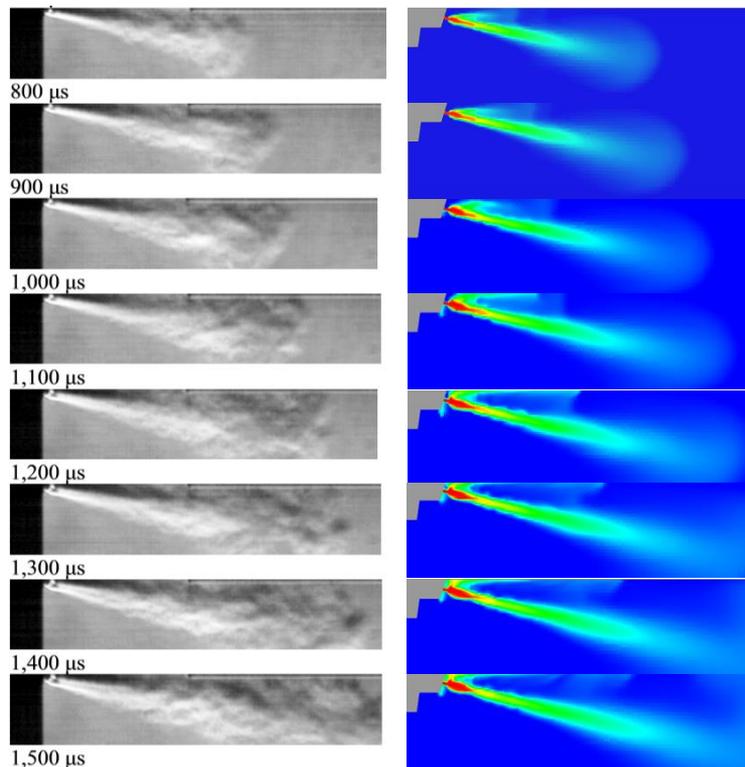
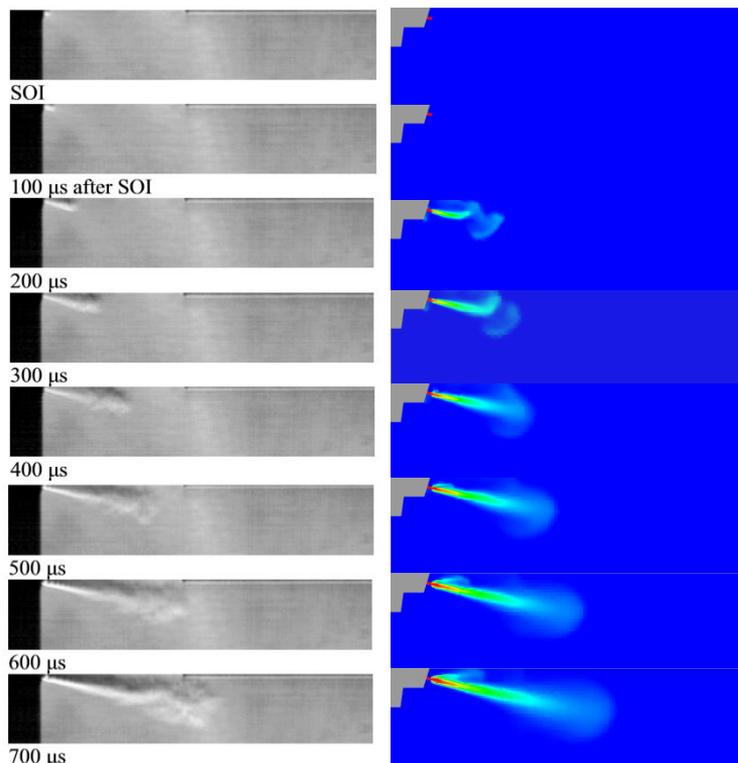


•单孔喷射;



•喷油器单孔改四孔, 引燃油量不变, 喷油速度相当;

# 二冲程双燃料船机模拟



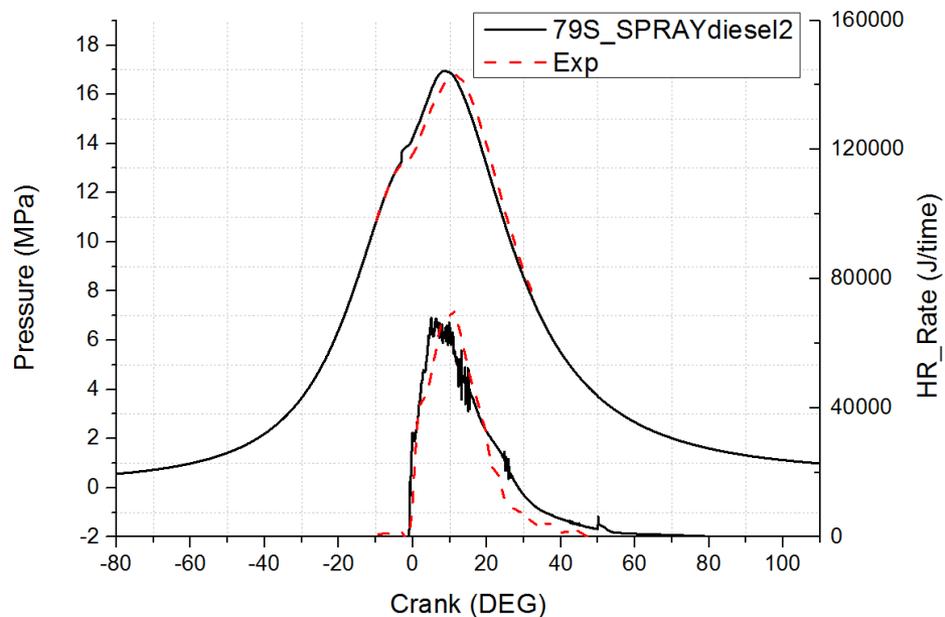
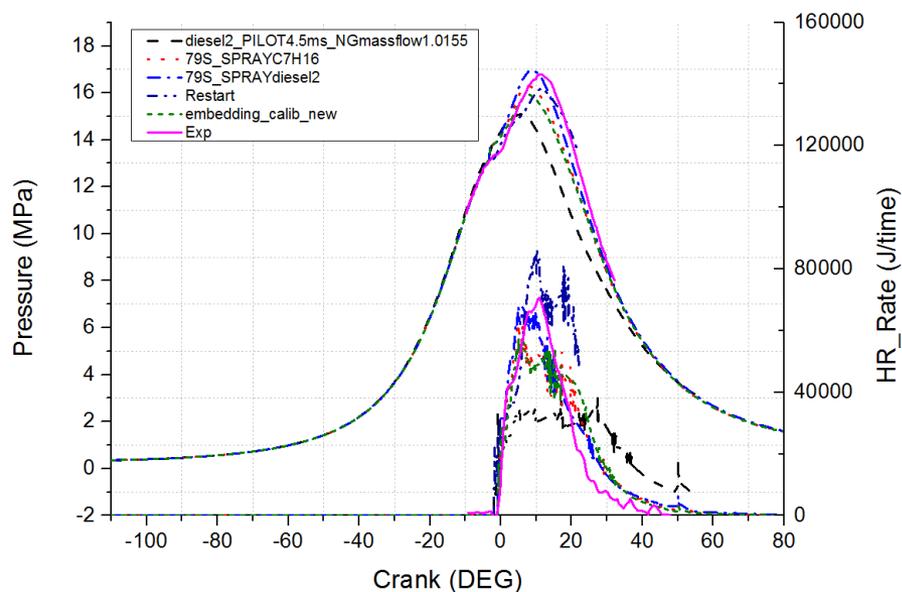
➢ 较好再现燃气喷束形态，捕捉到高压喷气射流中Mach disk和under-expanded现象，因此对超音速的气流运动模拟，建议采用0.125mm及以下网格尺寸

## 二冲程双燃料船机模拟

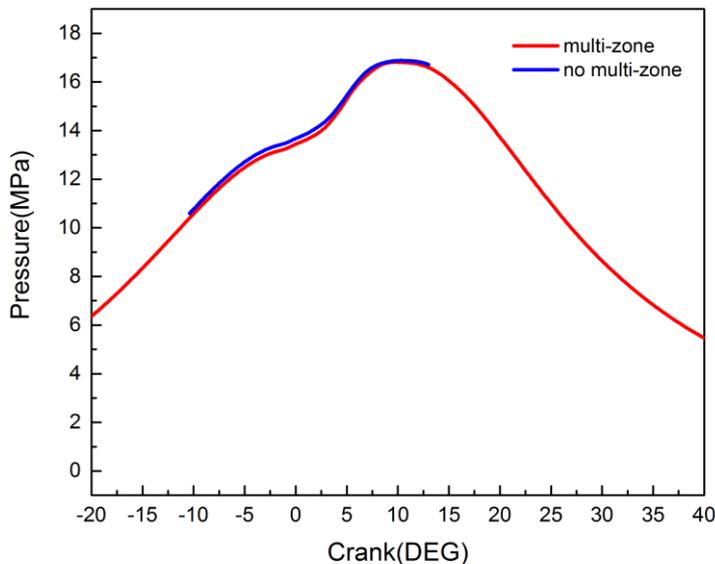
缸径 (mm)	500
冲程 (mm)	2200
转速 (rpm)	112; 75%负荷
压缩比	18.14
燃烧模型	SAGE (79组分, 262反应)
湍流模型	RANS k- $\epsilon$
模拟间隔 (deg CA)	-250~110 (一个完整循环)
液滴破碎模型	KH-RT
NO <sub>x</sub> 模型	Extended-Zeldovich Model
碳烟模型	Hiroyasu Model

天然气喷射压力 (bar)	281
天然气喷射温度 (K)	328
天然气喷射持续期 (deg CA ATDC)	-1~17.6
天然气喷射量 (g/cycle)	26.5
引燃油喷射始点 (deg CA ATDC)	-2
引燃油量 (g/cycle)	1.4
进气压力 (bar)	3.6bar
进气温度 (K)	317

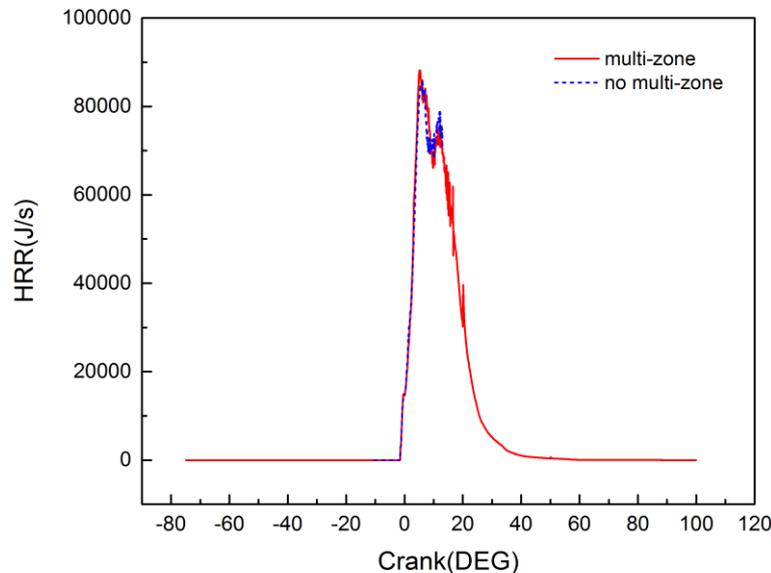
# 二冲程双燃料船机模拟



# 双燃料高压模型爆震模拟



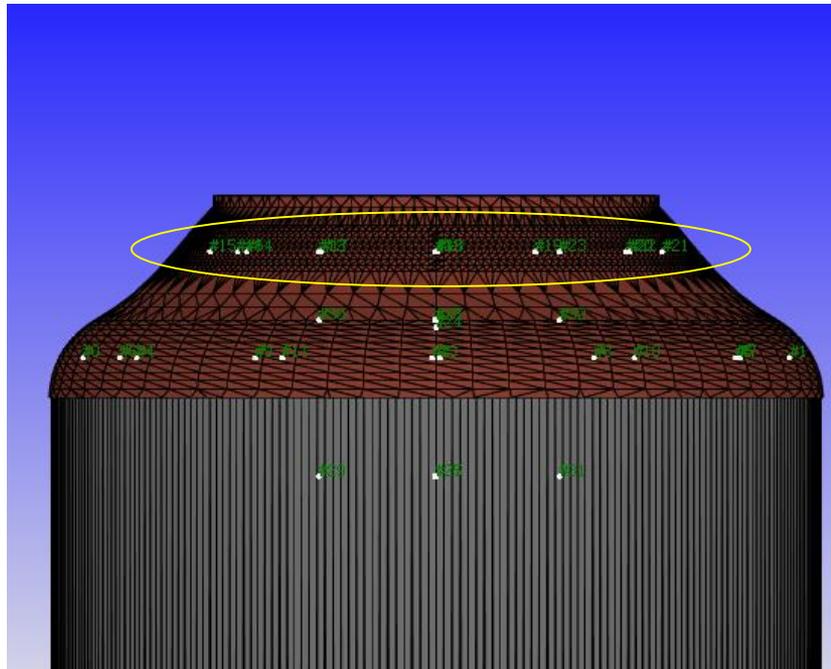
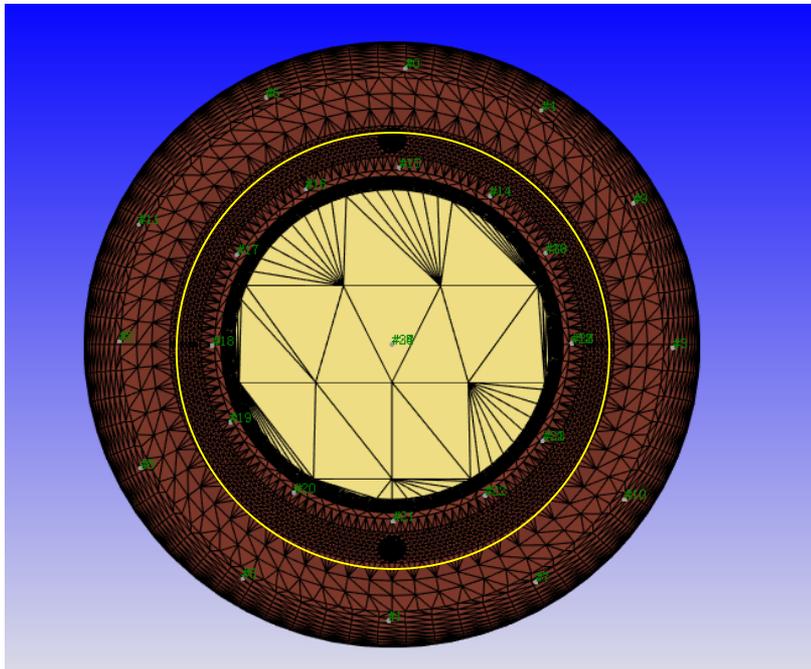
是否使用multi-zone对缸内压力的影响



是否使用multi-zone对放热率的影响

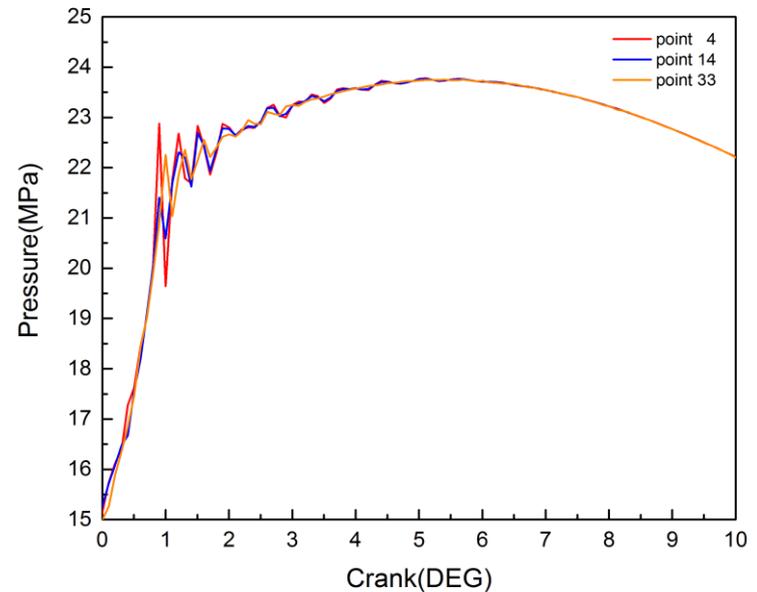
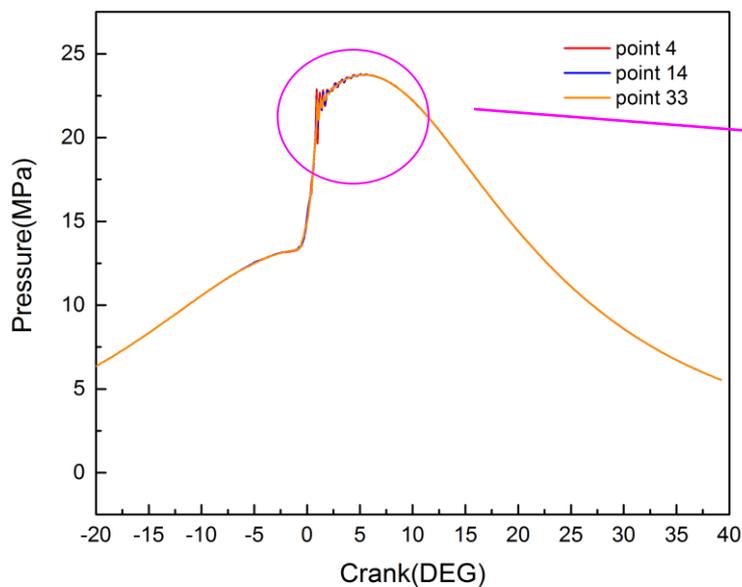
➤ 基于已标定完成的船机双燃料高压模型，对是否能使用multi-zone加速算法进行了验证，从图中可以看出，在船机双燃料高压模型中，multi-zone对燃烧的影响不是很大，误差在工程允许的范围，因此在船机模型中可以使用multi-zone加速算法。

# 双燃料高压模型爆震模拟



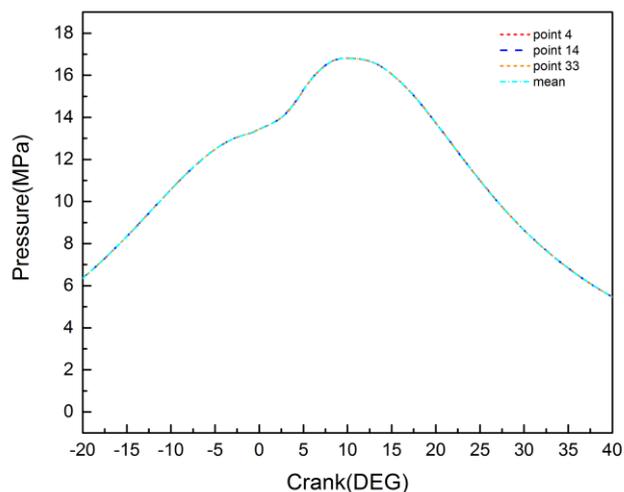
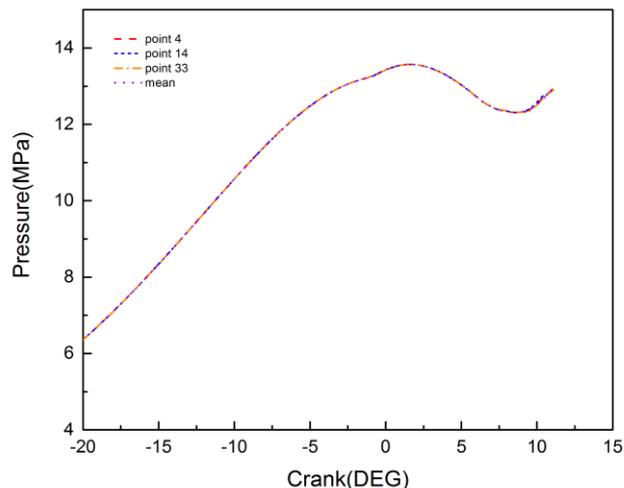
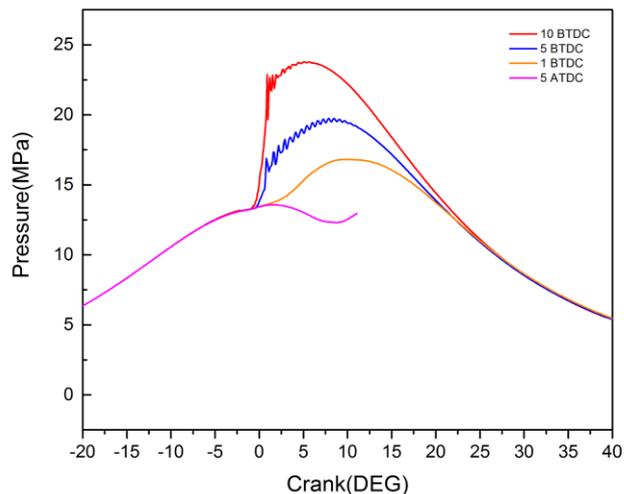
►通过分析船机缸内的燃烧形式，我们发现其在缸盖上部先行着火，因此我们在着火开始比较集中的区域布置了一圈监测点（如图黄圈所示区域），而后我们在燃烧室边缘区域也布置了一圈监测点用于研究末端小空间压力振荡的强度。

►基于此监测点设置，我们研究了天然气喷射相位对缸内压力振荡强度的影响，即通过改变天然气喷射相位使天然气实现部分预混合和扩散燃烧两种燃烧形式，研究了两种形式下缸内压力的变化规律。



➤ 图为天然气喷射相位为10 BTDC工况下不同监测点下缸内压力波动情况，其中point 4为最外围边缘区域的监测点，point 14为燃烧室上部区域的监测点，point 33为燃烧室中间区域的监测点，可以看出point 4压力振荡强度最大，point 33压力振荡强度最小，这与预期的边缘区域空间小振荡强度大，中部区域空间大振荡强度小的现象一致。

# 双燃料高压模型爆震模拟



➤ 图1为监测点4监测的不同天然气喷射时刻缸内压力分布图，从图中可以看出天然气喷射越提前缸内压力峰值越大，压力升高率越大，同时knock强度越大，而当天然气在柴油之后喷，即主要是扩散燃烧的形式下，没有压力振荡发生。

➤ 图2为标定工况下，监测点监测压力和平均压力的对比图，可以看出其压力值一致，即没有knock发生时，缸内监测点监测压力即缸内平均压力。

➤ 图3是天然气喷射相位为5 ATDC时缸内平均压力和监测点压力对比图，可以发现与图2结论一致。

- 感谢IDAJ的支持
- 感谢内燃机燃烧学国家重点实验室的支持
- 感谢科技部创新工程项目的支持

感谢聆听！

周磊 Lei.zhou@tju.edu.cn

