第十一届内燃机可靠性技术国际研讨会
The 11th International Conference of ICE Reliability Technology

双直喷式碳中和发动机燃烧技术探索

Exploration on combustion technology of dual-direct-injection carbon neutral engine

隆 武 强
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碳中和

时空尺度、经济规模最大

研究背景 (Background)

1. 国际

- 国际海事组织IMO于2020年批准《甲醇/乙醇燃料船舶安全暂行指南》。
- 德国政府闭环碳循环C^3行动，研究基于甲醇的气候中性燃料；印度甲醇经济规划蓝图，M15, M100, 甲醇船舶等；以色列（甲醇汽油），意大利（甲醇乙醇汽油），冰岛（纯甲醇）……

3. 地方

- 2020年，山西省工信厅等12家单位发布《加快推进甲醇汽车产业发展和全省域推广应用的实施方案》，指出“2022年底，全省甲醇汽车超过2万辆，甲醇加注站200座以上”。
- 2022年，贵州省发改委等17家单位发布《支持在全省推广应用甲醇汽车的若干政策措施》，明确指出”2025年底，甲醇汽车保有量达5万辆，甲醇加注站200座”。

2. 国家

2017年

船级社：船舶应用替代燃料指南

2019年

工信部等八部委：关于在部分地区开展甲醇汽车应用的指导意见

2021年

- 工信部：十四五工业绿色发展规划
- 交通部：绿色交通十四五发展规划

2022年

- 船级社：《船舶应用甲醇/乙醇燃料指南》《船舶应用氨燃料指南》
- 工信部等五部委：关于加快内河船舶绿色智能发展的实施意见

研究背景 (Background)

- **甲醇车：我国甲醇乘用车和商用车合计保有量达3万辆，成为全球最大的甲醇汽车消费市场。**



- **甲醇船：**

低速机船舶—丹麦马士基19艘，法国达飞6艘，中远海控12艘，招商轮船6艘等等，均使用曼恩低速机，累计订单78台套，推进功率覆盖了4 MW至82 MW。

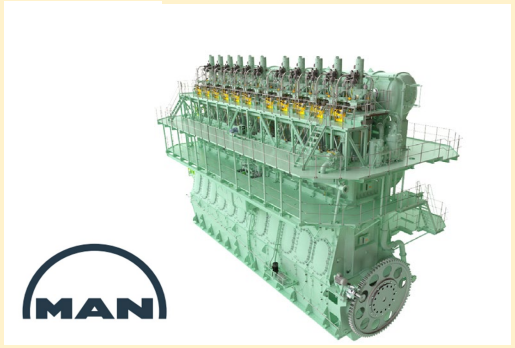
中速机船舶—荷兰Van Oord海上风电安装船，5台套瓦锡兰甲醇中速机。

高速机船舶—均在开发和示范中……

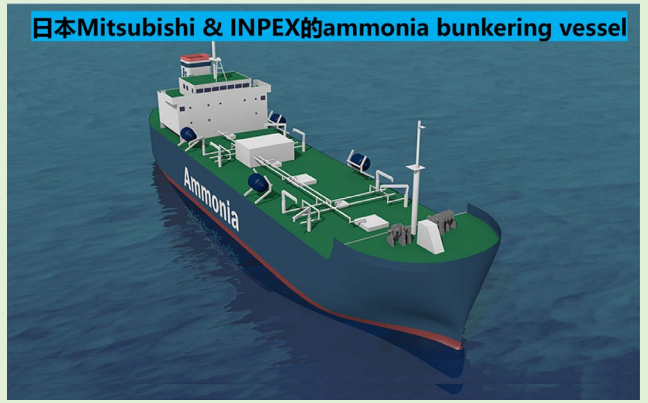

研究背景 (Background)

口 应用

曼恩和瓦锡兰正在研发中，计划2024年示范。

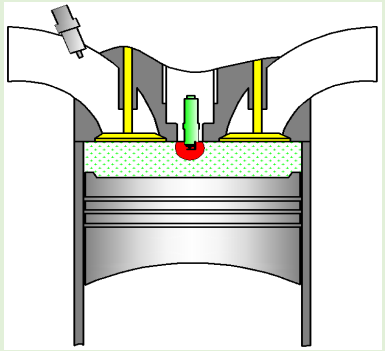


口 配套

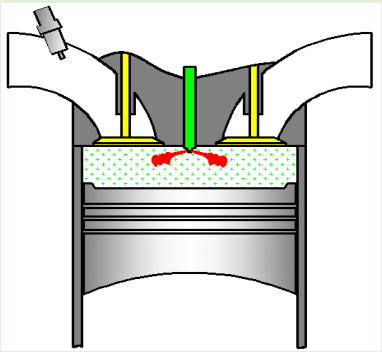


研究背景 (Background)

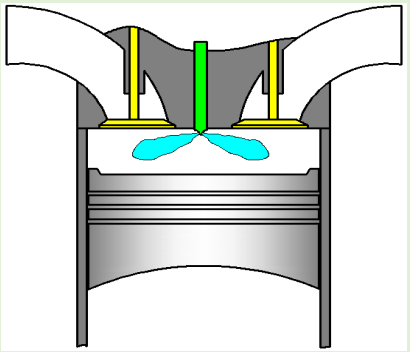
现有氨发动机技术：



点燃式预混合燃烧
Spark ignition premixed combustion



引燃式预混合燃烧
Pilot ignition premixed combustion



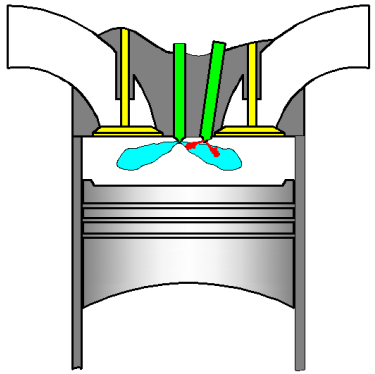
DME+NH3压燃
DME+NH3 Compression ignition

低压策略下氨燃料模式与纯柴油模式的发动机特性对比

热效率 Thermal efficiency	低于纯柴油模式 Lower than diesel mode
燃烧效率 Combustion efficiency	容易出现不完全燃烧 Incomplete combustion
NOx 排放 NOx emission	明显高于纯柴油模式 Higher than diesel mode
氨燃料替代率 ASR	低 Low

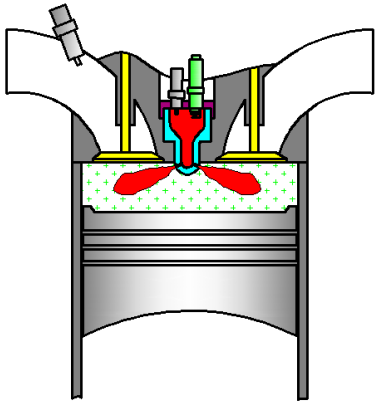
研究背景 (Research background)

柴油微喷引燃式甲醇/氨发动机
Diesel micro-pilot methanol/ammonia engine



- ✓ 高替代率
  High substitution rate
- ✓ 高热效率
  High thermal efficiency

点火室式甲醇/氨发动机
Ignition chamber type methanol/ammonia engine



- ✓ 高燃烧速率
  High combustion rate
- ✓ 高热效率
  High thermal efficiency

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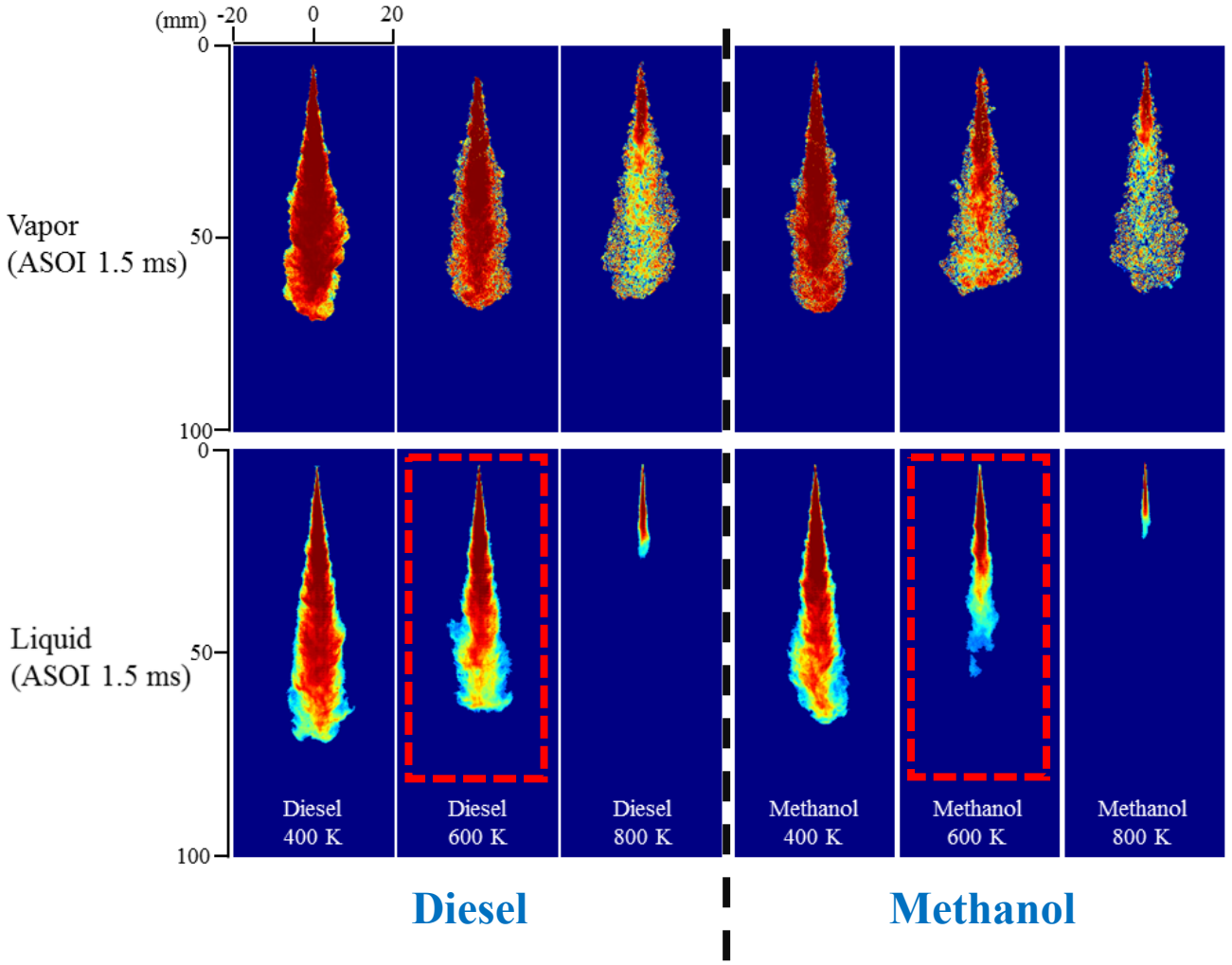
甲醇高压喷雾特性 (Characteristics of Methanol High-pressure Spray)

环境温度影响 (Impact of ambient temperature)



- 低温400 K和高温800 K: 甲醇和柴油喷雾的气/液喷雾形态相仿。

400 K and 800 K: The morphology of methanol and diesel sprays are similar.

- 中等温度600 K: 甲醇可以实现较好的蒸发，即高压直喷甲醇可以实现良好的混合气。

600 K: Methanol can achieve better evaporation, and high-pressure direct-injection methanol can achieve good fuel-air mixture.

甲醇高压喷雾特性 (Characteristics of Methanol High-pressure Spray)

孔径影响 (Impact of nozzle diameter)

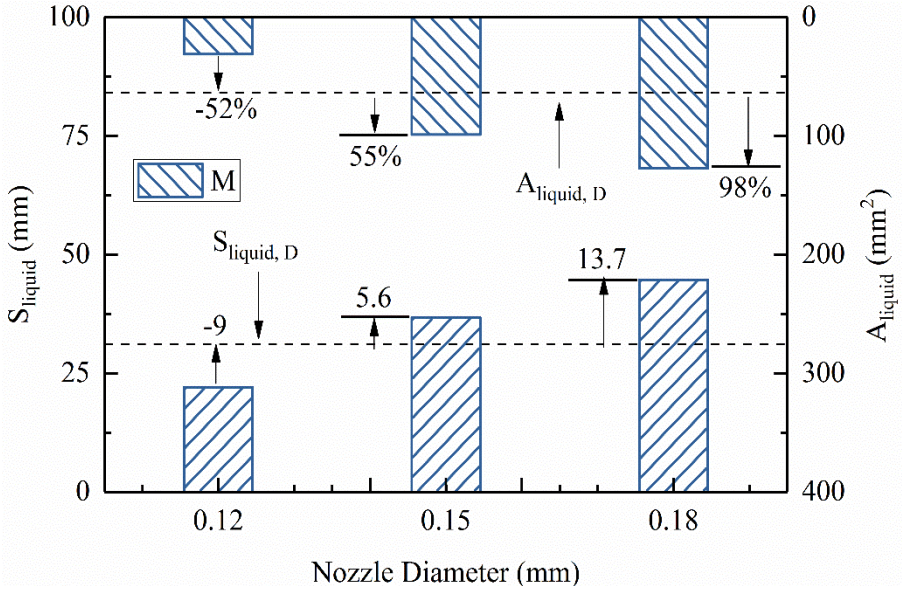
Vapor: Penetration--Methanol>Diesel 20%-30%

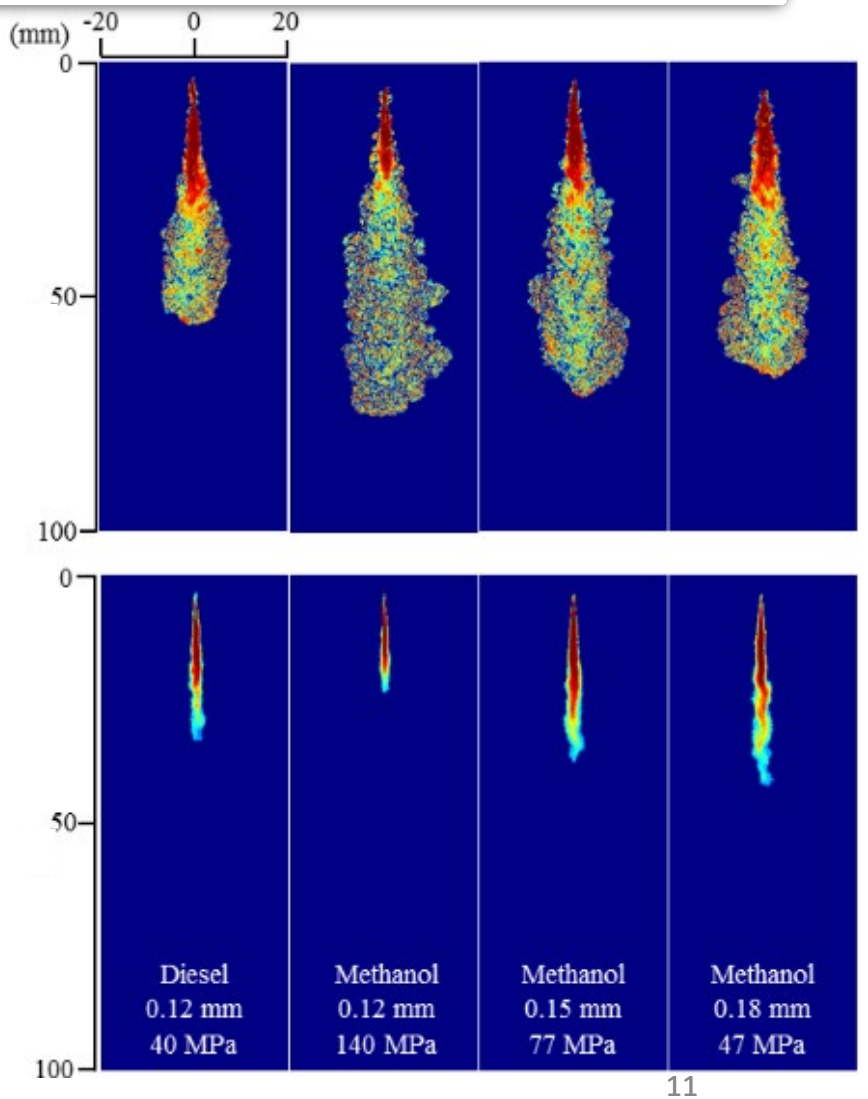
Cone angle--Methanol>Diesel 15%-25%

Area--Methanol>Diesel 70%-110%

Liquid: Affected by injection pressure and nozzle diameter.

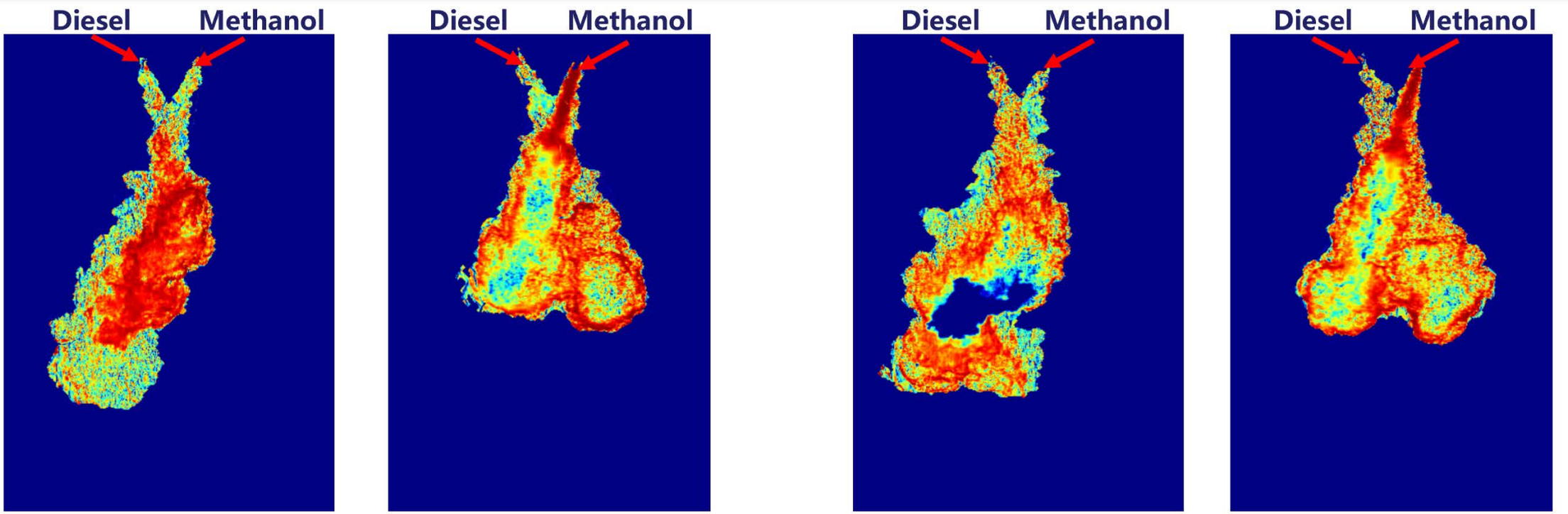
Principles: Minimum design of methanol nozzle diameter with maximum injection pressure.





柴油引燃甲醇燃烧特性 (Characteristics of Diesel Pilot Methanol Combustion)

甲醇预混合和扩散燃烧 (Methanol premixed and diffusion combustion)



$t_{combustion}$ =1.7ms　　$t_{combustion}$ =0.5+1.8ms　　$t_{combustion}$ =1.5ms　　$t_{combustion}$ =0.8+1.8ms

T= 850 K　　T= 900 K

甲醇预混合燃烧具有更快的燃烧速度，未燃甲醇区域较多。

Methanol premixed combustion has faster combustion rate and more unburned methanol regions.

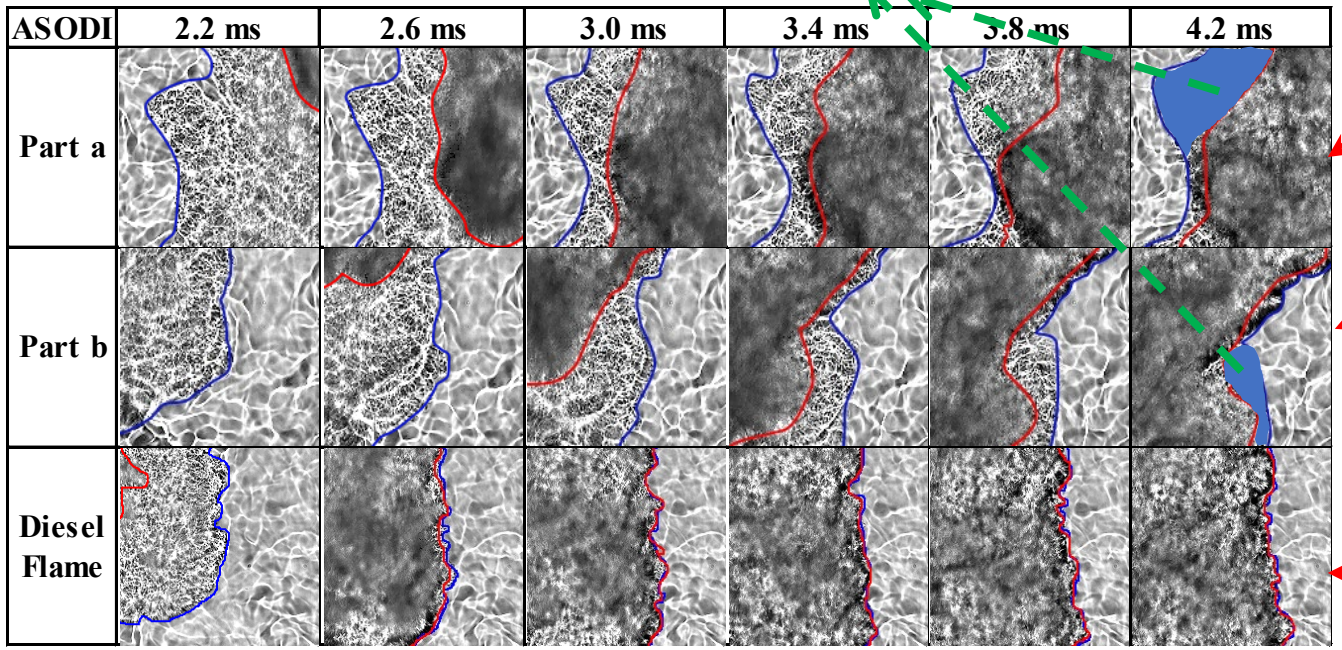
柴油引燃甲醇燃烧特性 (Characteristics of Diesel Pilot Methanol Combustion)

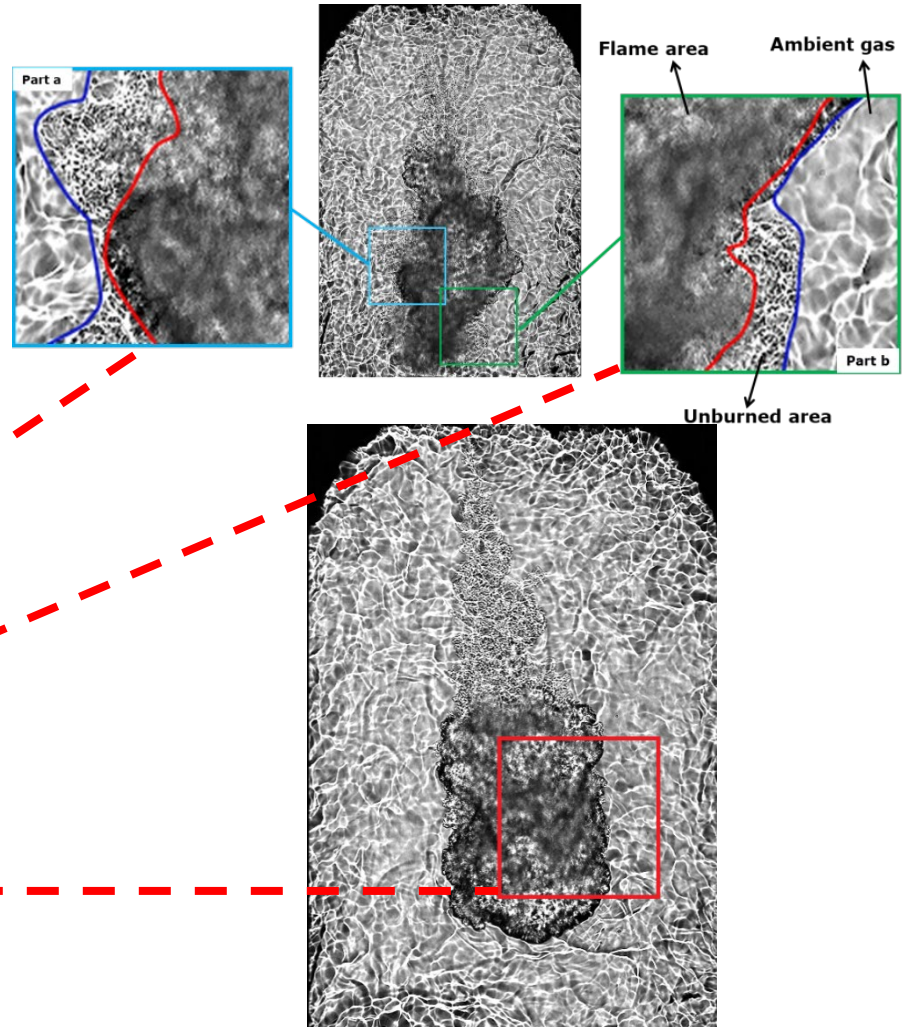
甲醇预混合燃烧 (Methanol premixed combustion)

大量HC和CO排放
Large amounts of HC and CO emissions

↓

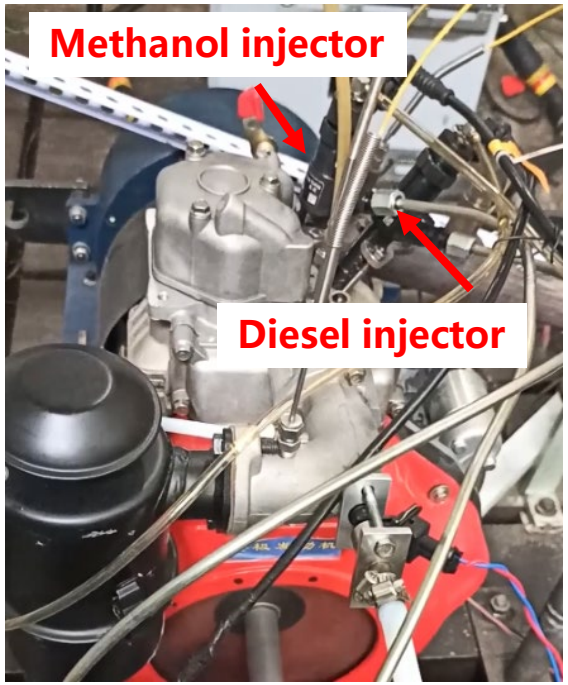
局部未完全燃烧的甲醇
Local unburnt methanol

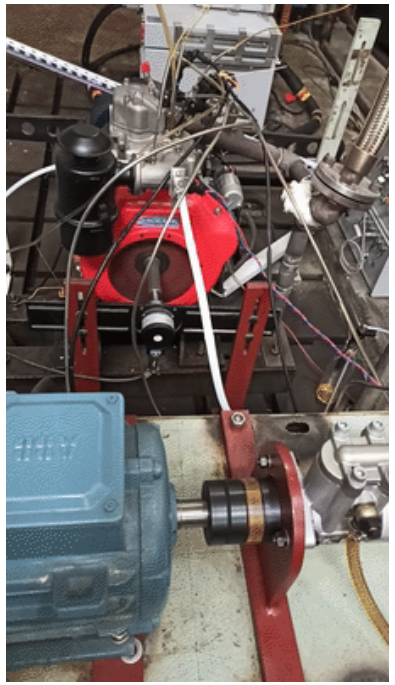




甲醇发动机试验 (Test of Methanol Engine)

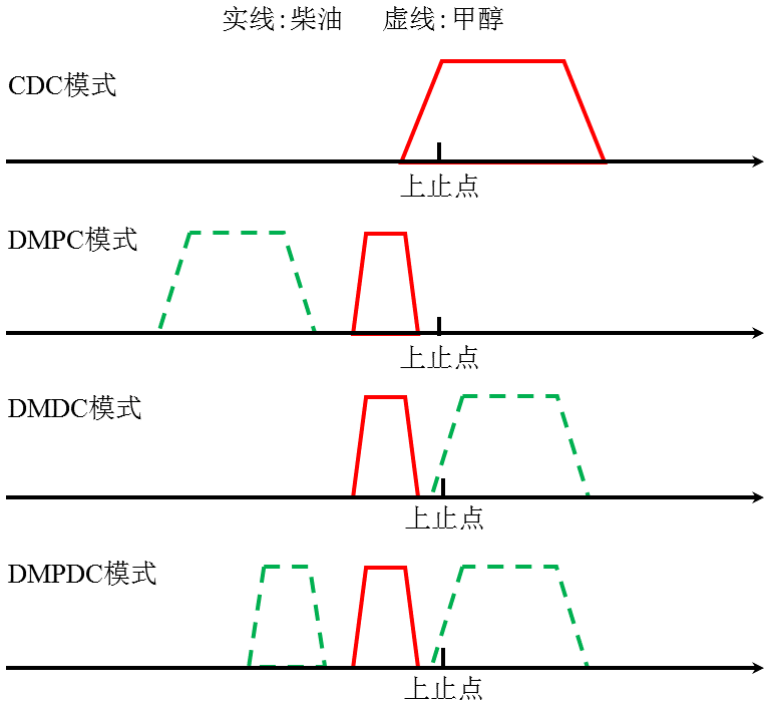
甲醇/柴油双直喷原理样机整机试验
Test of methanol/diesel dual-direct injection prototype engine





原理样机

Prototype engine

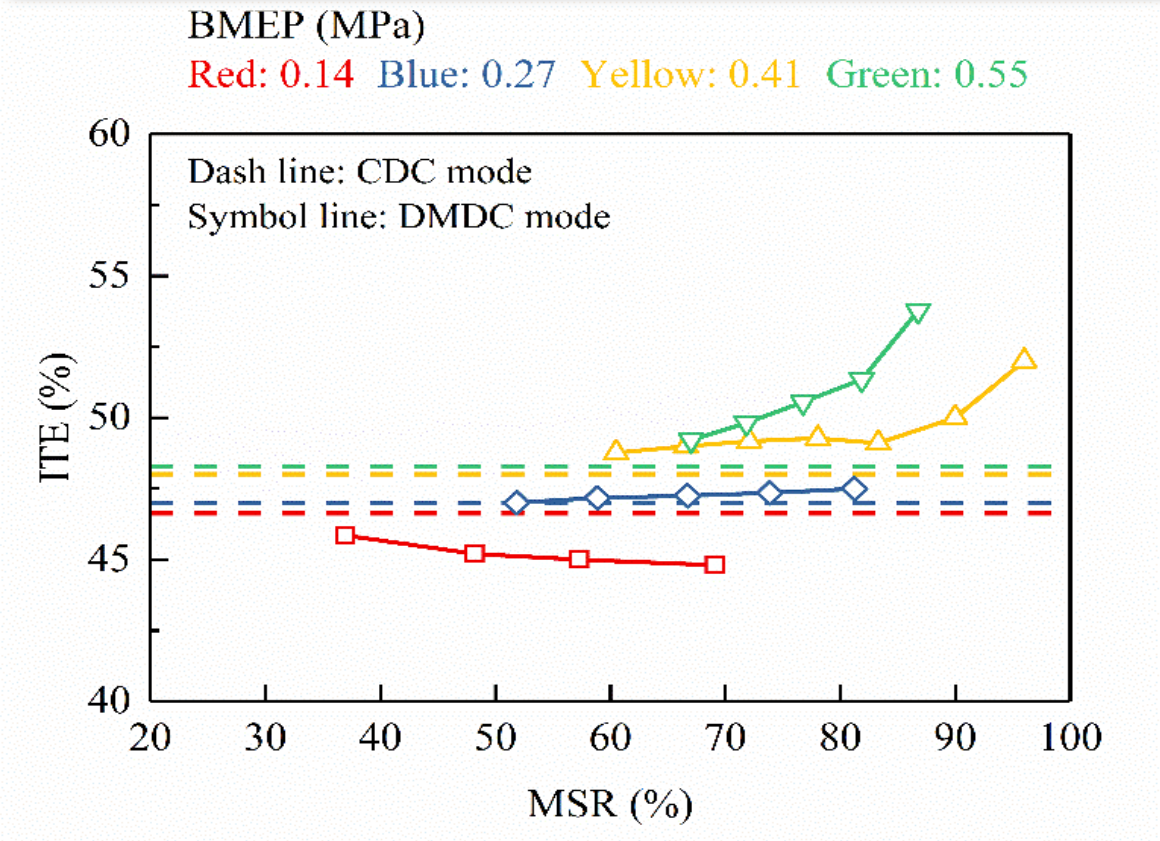


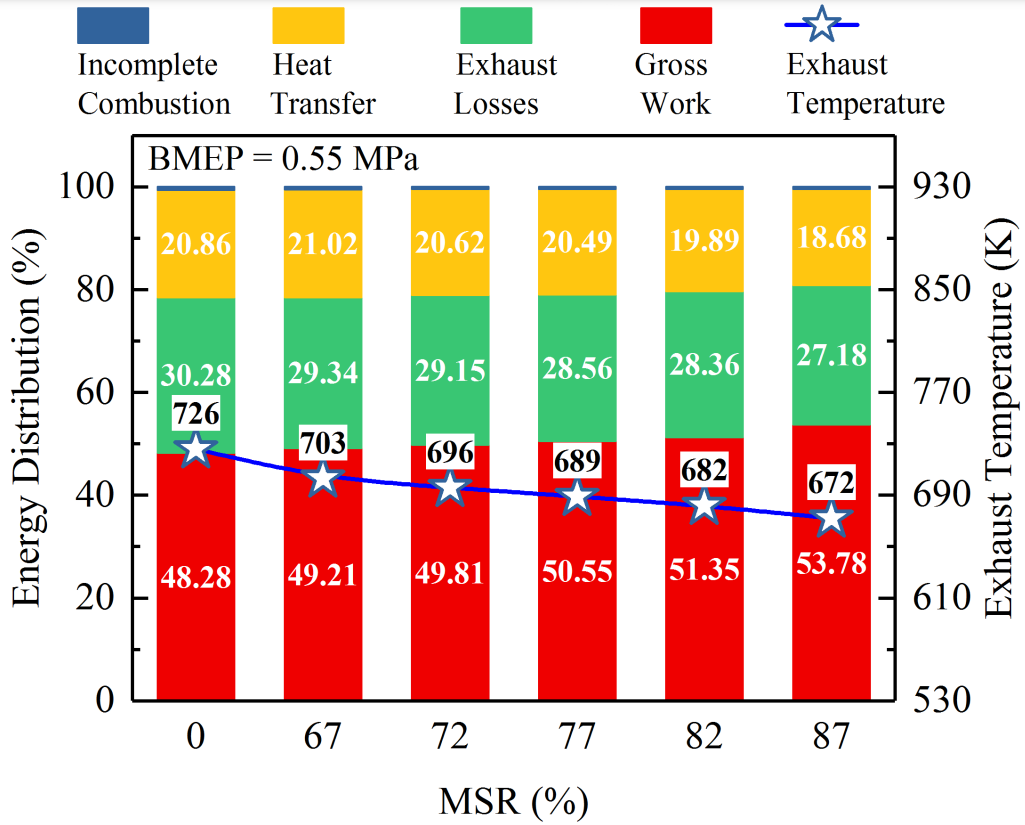
燃烧模式定义

Combustion mode definition

甲醇发动机试验 (Test of Methanol Engine)

CDC模式与DMDC模式对比 (CDC vs. DMDC)

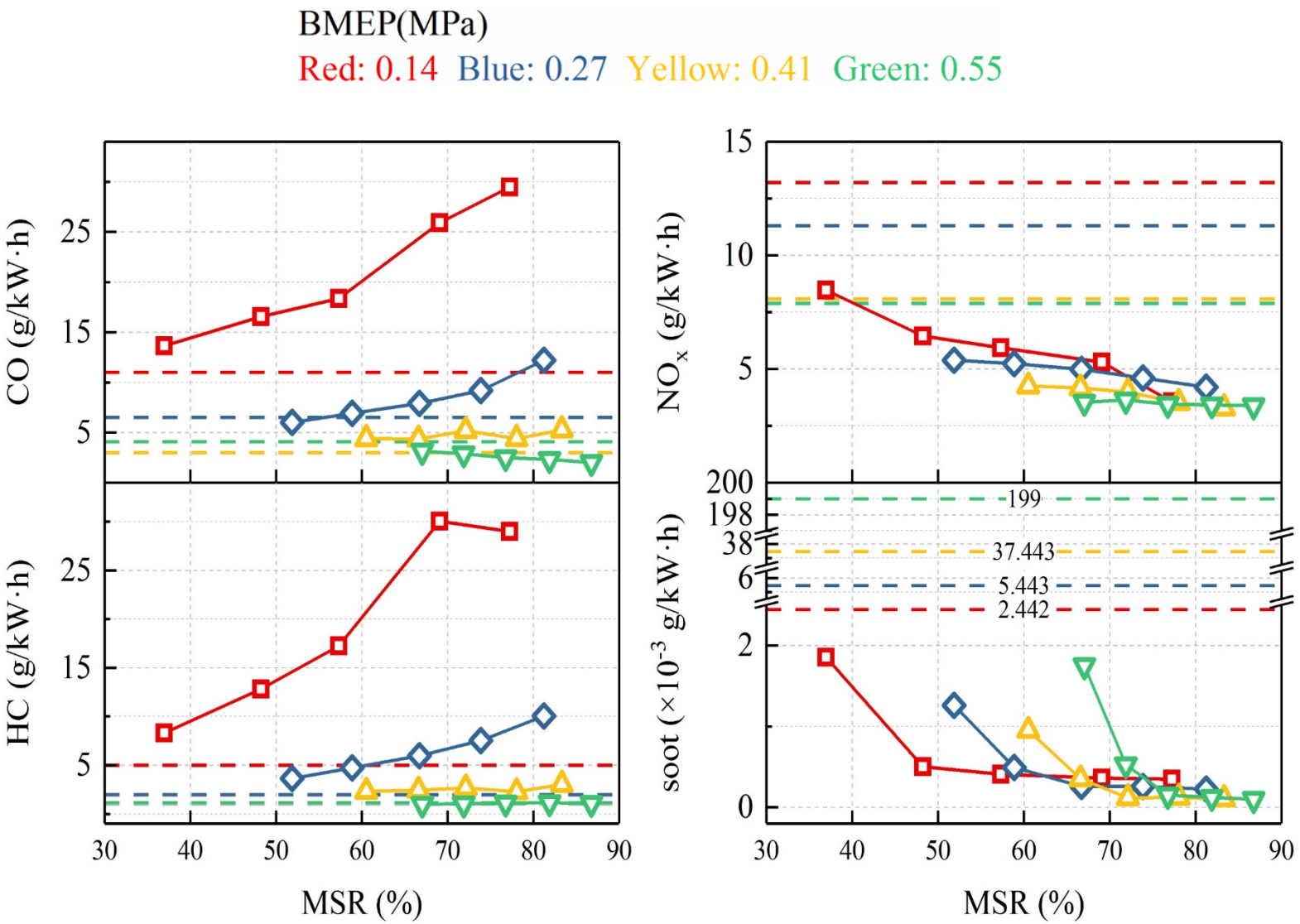




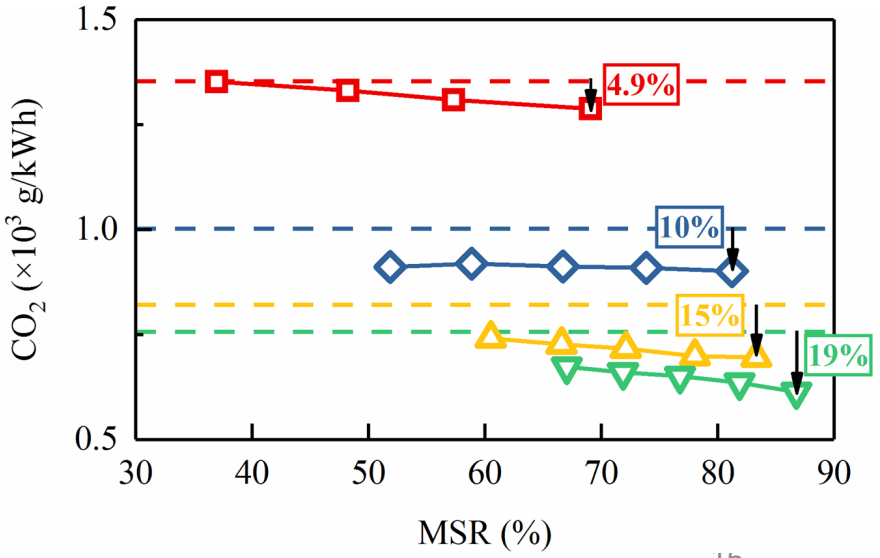
Thermal Efficiency: 25% load--DMDC<CDC; 100% load-- DMDC>CDC 10%

Exhaust/Heat losses: 100% load--DMDC<CDC 10%

甲醇发动机试验 (Test of Methanol Engine)

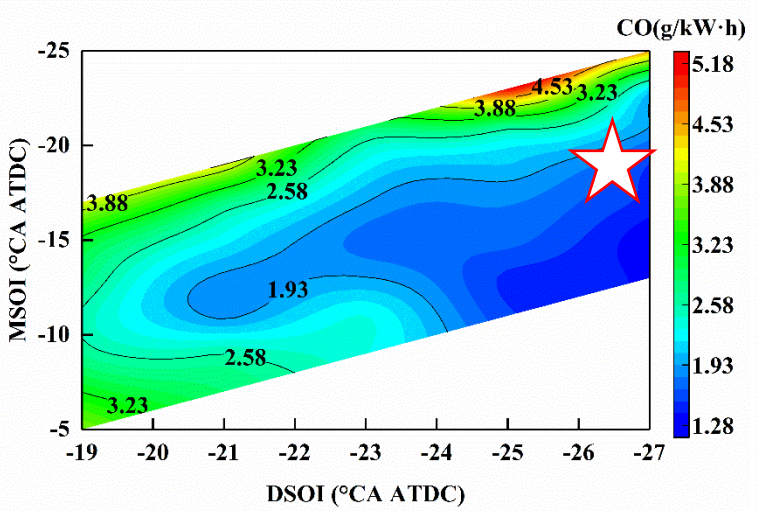


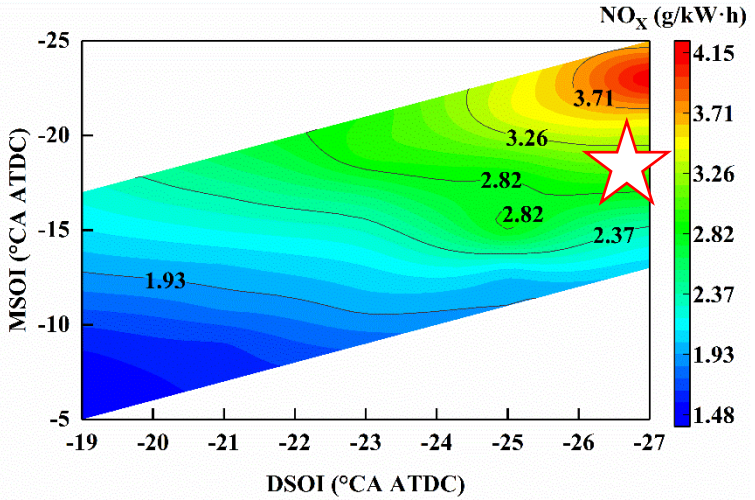
- HC: Low load ↑ several times
  Full load ↓ 5%
- CO: Low load ↑ several times
  Full load ↓ 50%
- NOx: ↓ 60%
- soot : ↓ 99%
- CO_2: Full load ↓ 19%

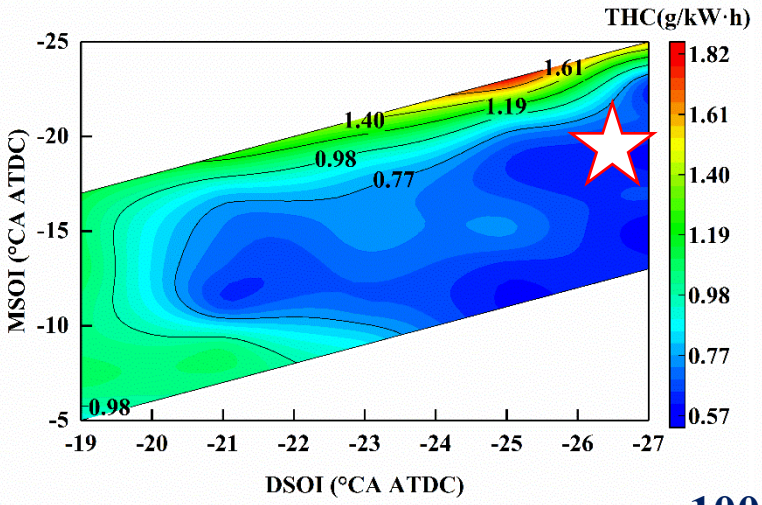


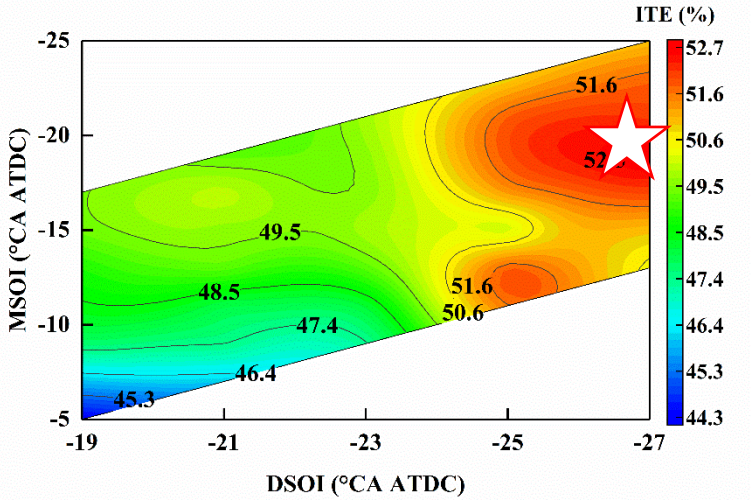
甲醇发动机试验 (Test of Methanol Engine)

DMDC模式喷射正时研究（ Injection Timing in DMDC mode）









-100%负荷-

DMDC模式可以得到最佳ITE的同时，兼具相对较少的CO和THC以及NOx排放。

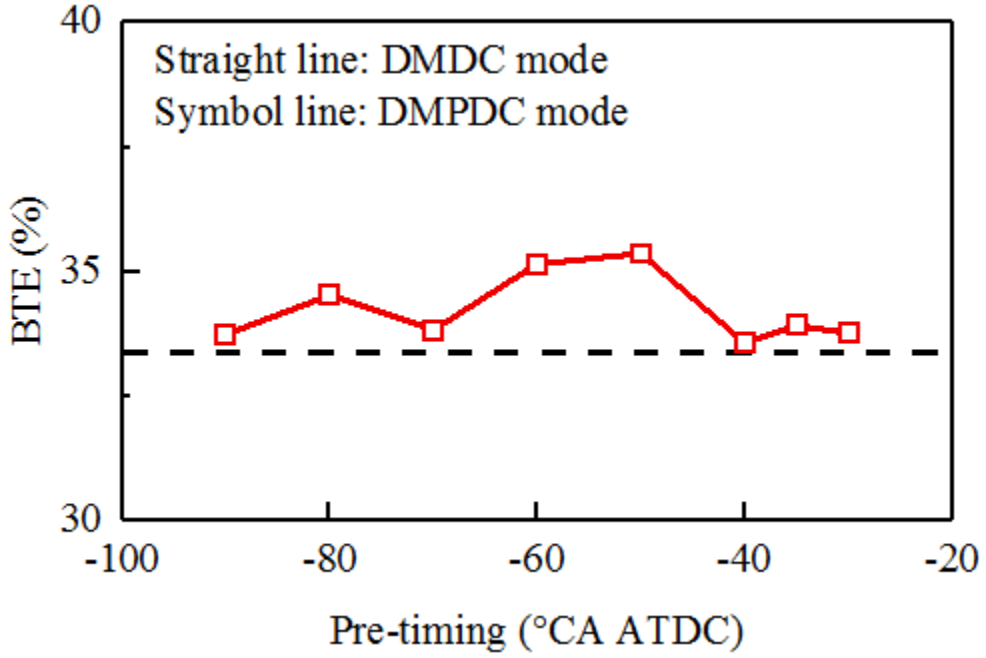
DMDC mode can obtain the best ITE with relatively less CO, THC and NOx emissions.

甲醇发动机试验 (Test of Methanol Engines)

DMPDC模式研究 (DMPDC mode)

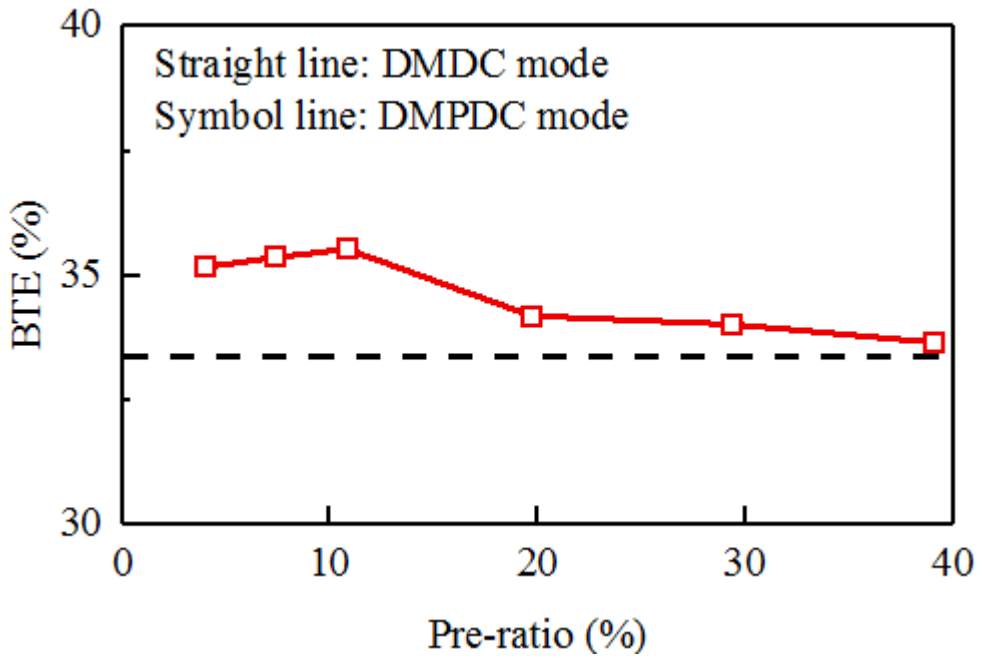
不同预喷射正时（预喷射占比10%）

Different pre-injection timing (pre-injection ratio=10%)



不同预喷射占比（预喷射正时-50 °CA ATDC ）

Different pre-injection ratio (pre-injection timing=-50 °CA ATDC)



DMPDC模式相对DMDC模式热效率再提升5%

Thermal efficiency: DMPDC>DMDC 5%

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一 研究背景
Background

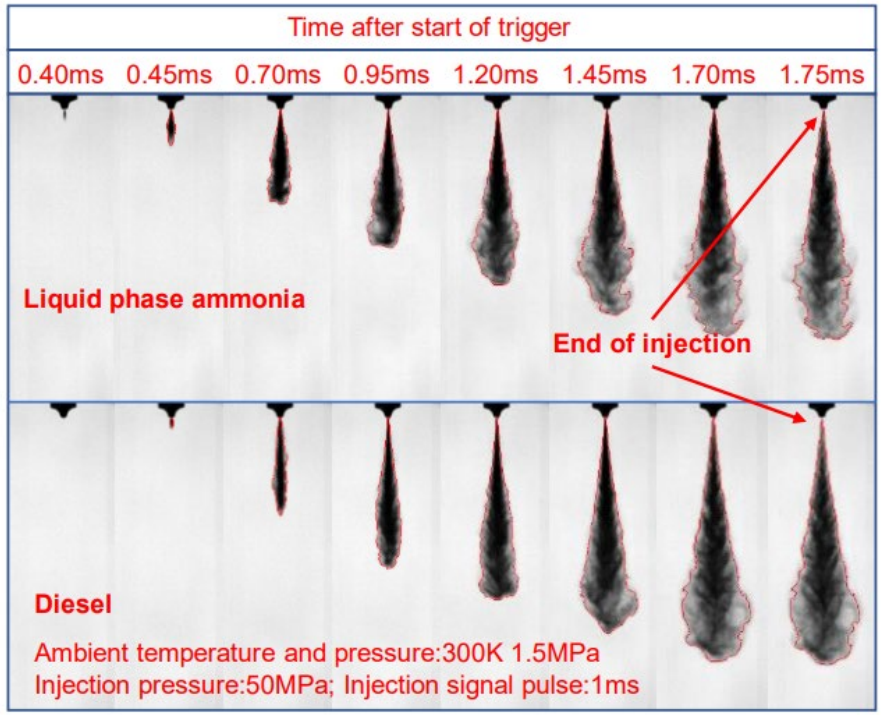
二 燃烧技术探索
Exploration of combustion technologies

- 甲醇发动机研究
  Study of methanol engine
- 氨发动机研究
  Study of ammonia engine

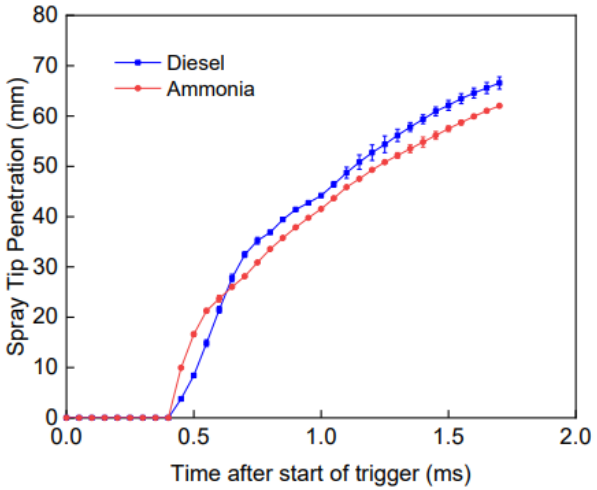
三 结论
Conclusions

氨喷雾和燃烧特性研究 (Characteristics of Ammonia Spray and Combustion)

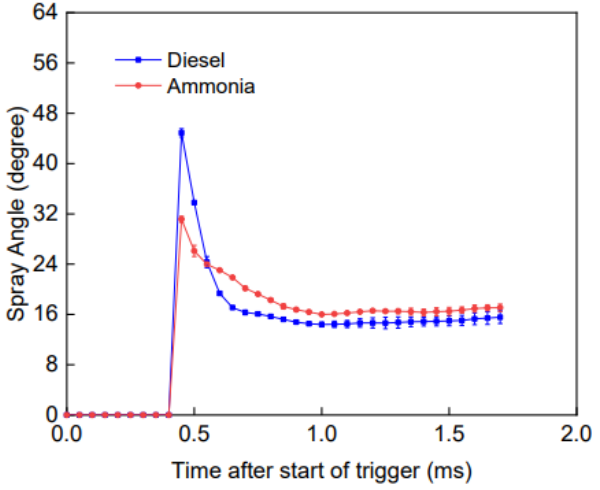
液氨喷雾特性（Characteristics of liquid ammonia spray）



(a) Liquid phase spray images



(b) Spray tip penetration



(c) Spray angle

与柴油喷雾相比：起始喷射阶段，液氨喷雾贯穿距大、喷雾锥角小。

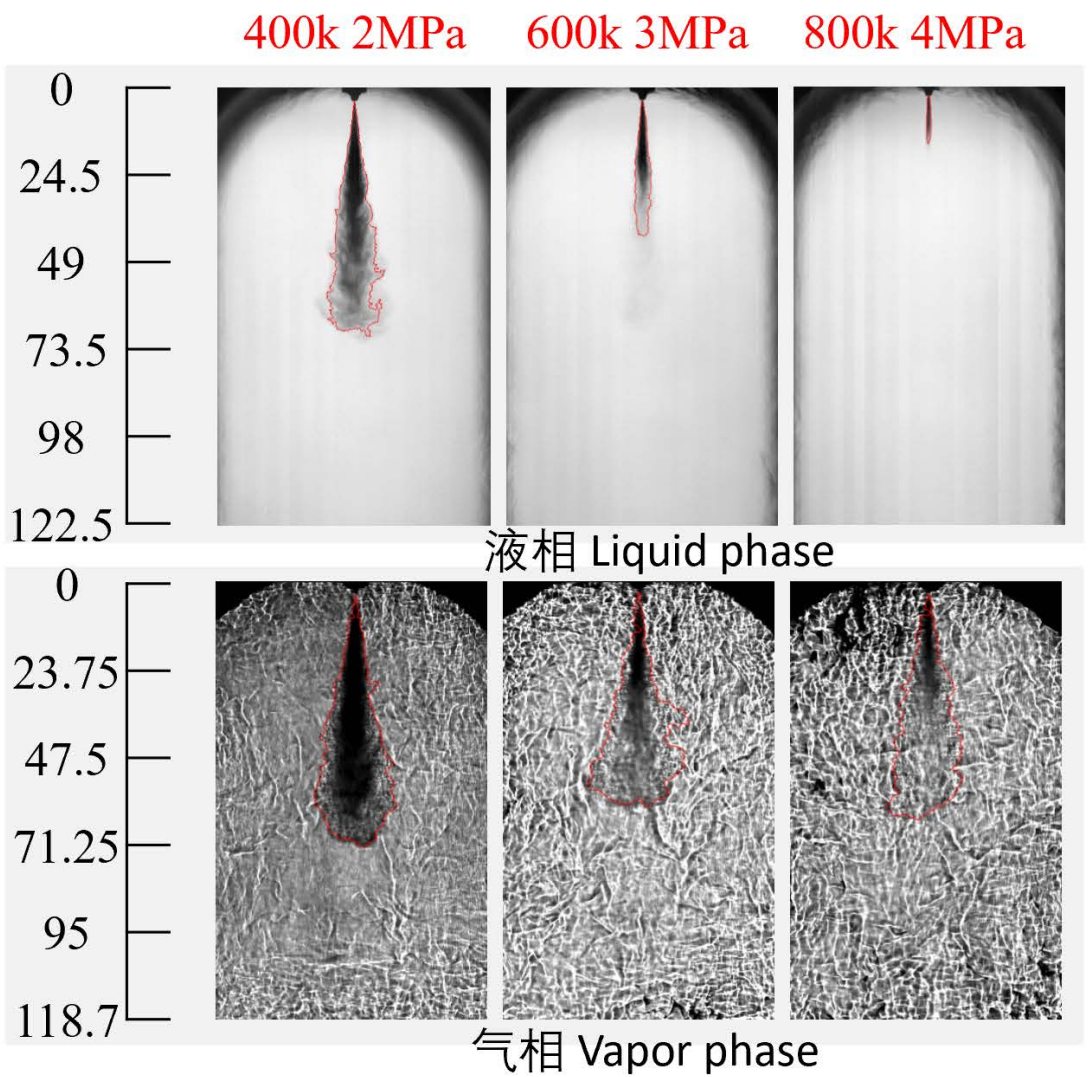
At the initial stage of injection, the spray penetration of liquid ammonia is larger and the spray cone angle is smaller, compared with diesel spray.

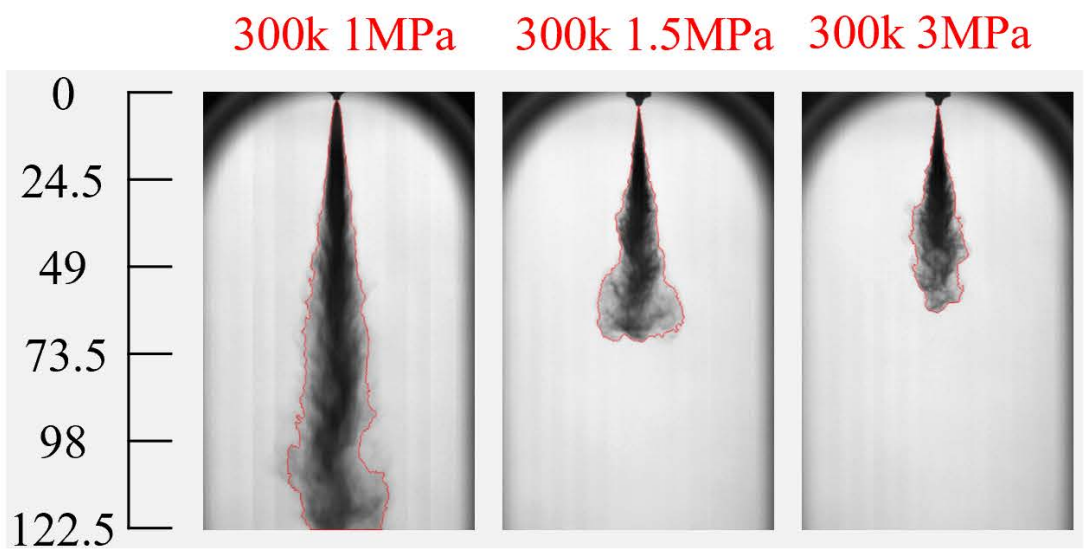
与柴油喷雾相比：喷雾发展阶段，液氨蒸发快，导致更短的喷雾贯穿距和更大的喷雾锥角。

At the developmental stage of spraying, liquid ammonia evaporated quickly, resulted in shorter spray penetration and larger spray cone angle, compared with diesel spray.

氨喷雾和燃烧特性研究 (Characteristics of Ammonia Spray and Combustion)

液氨喷雾特性（Characteristics of liquid ammonia spray）



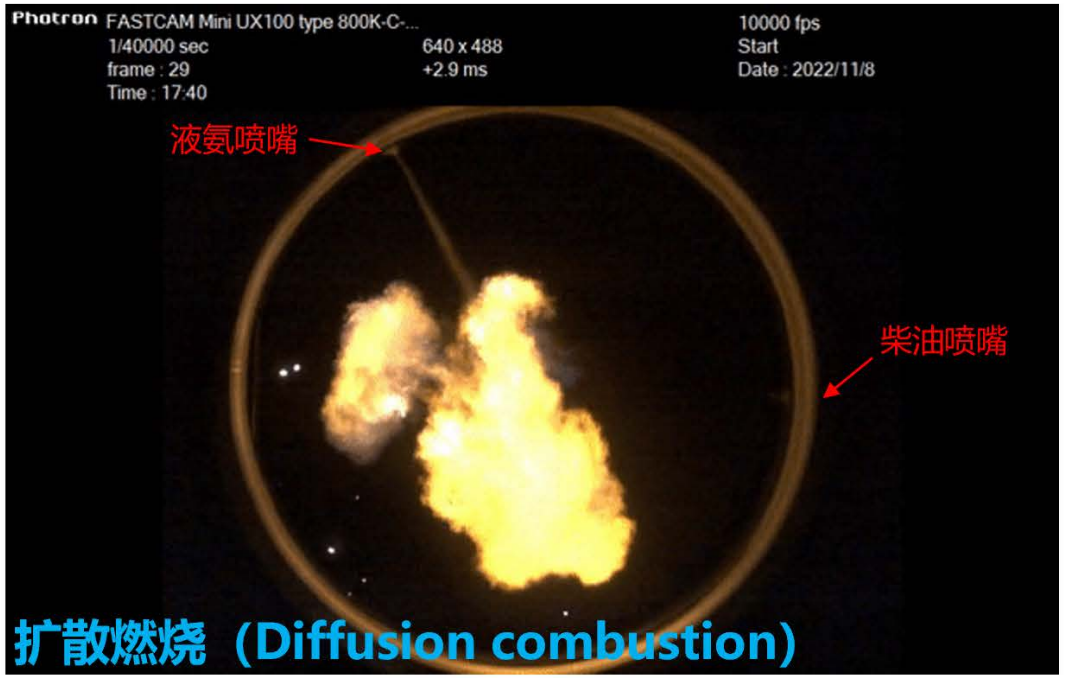


环境密度相同时，随着温度和压力的提高，喷雾气相喷雾的贯穿距和喷雾投影面积没有显著变化，但喷雾液相贯穿距和投影面积显著减小。

Liquid phase spray penetration and spray area decreased dramatically with the increment of ambient pressure and temperature.

氨喷雾和燃烧特性研究 (Characteristics of Ammonia Spray and Combustion)

液氨扩散燃烧可视化试验
(Visualization study of ammonia diffusion combustion)

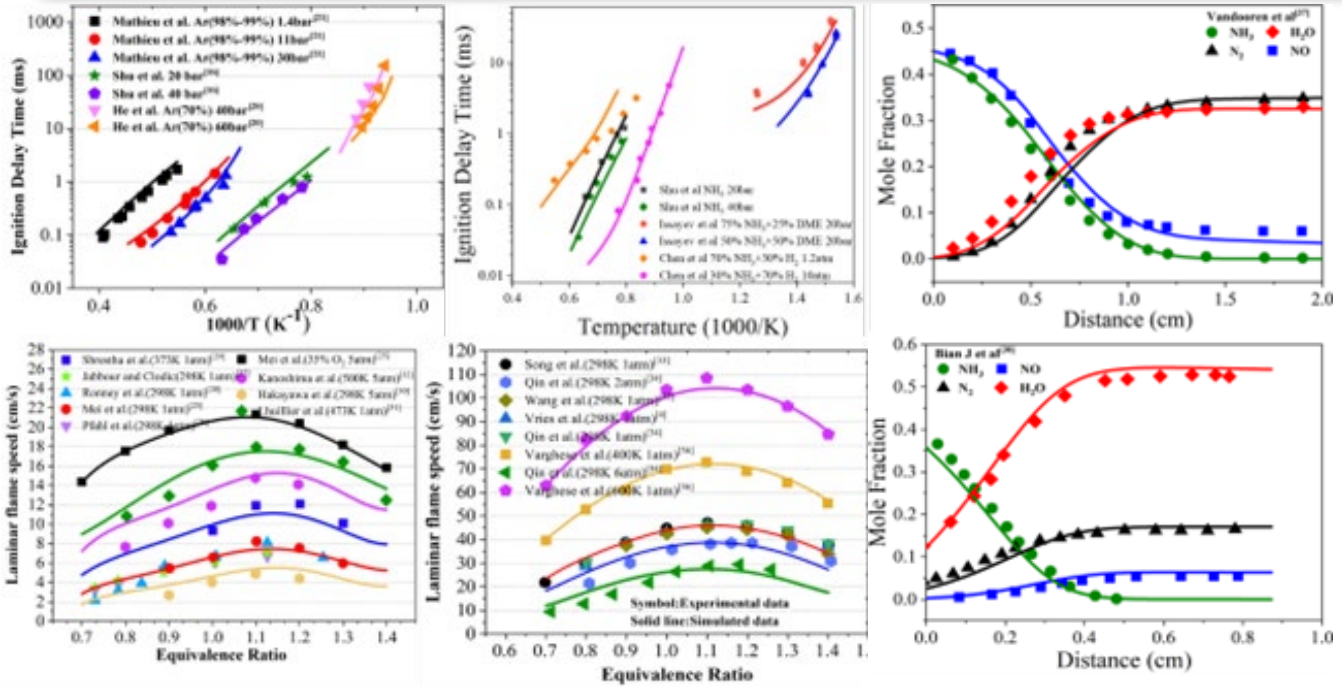


快压机试验表明，射流引燃液氨直喷扩散燃烧具有燃烧速度快、燃烧效率高的优势。

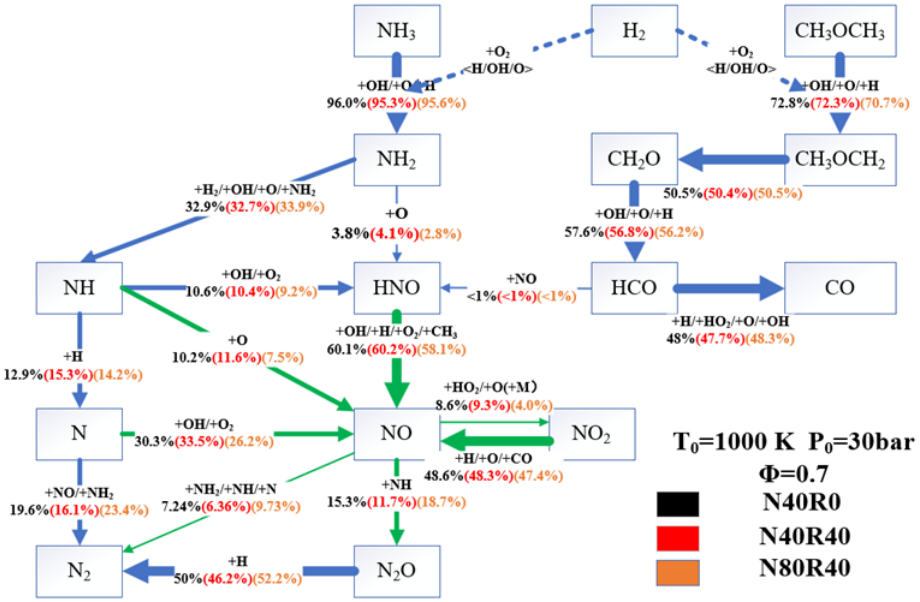
Ammonia diffusion combustion has advantages of high combustion rate and combustion efficiency.

氨燃烧机理研究 (Ammonia combustion mechanism)

氨氢燃料反应机理和NO生成与还原过程
（Ammonia combustion mechanism and NO generation and reduction）



氨氢、低碳添加剂等混合燃料LBV、着火延迟时间及NO浓度预测



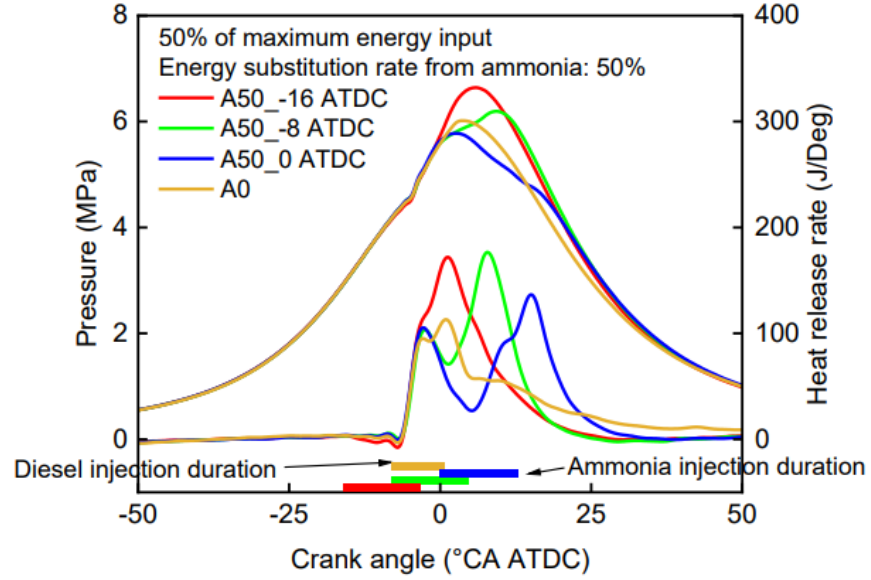
氨燃烧中NO生成与还原过程

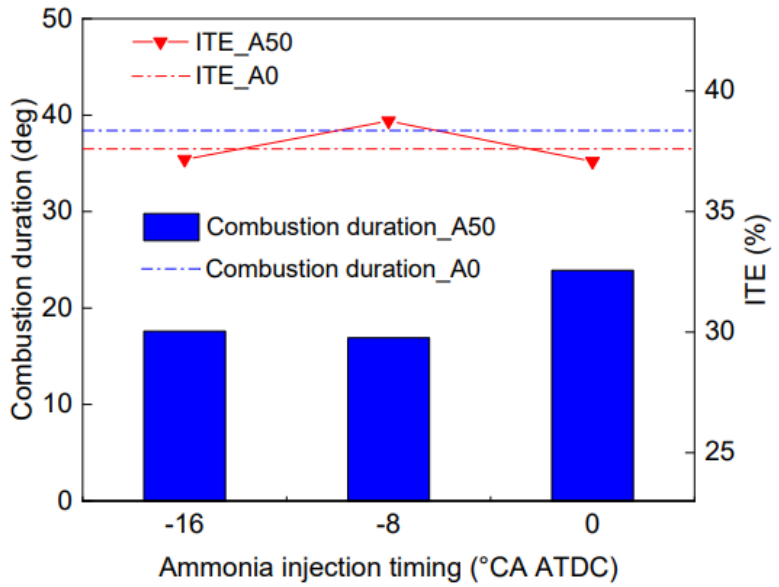
1. 开发了氨氢、氨/低碳混合燃料燃烧简化化学反应机理，预测精度高；
2. 氨燃烧过程的燃料型NO是一大难题，机理中阐明了其生成与还原过程。

Meng, X., et al., Understanding of combustion characteristics and NO generation process with pure ammonia in the pre-chamber jet-induced ignition system. Fuel, 2023. 331: p. 125743.

双直喷氨发动机研究 (Ammonia/diesel dual-direct-injection two-stroke engine)

直喷液氨的不同燃烧模式（Different combustion modes）





(b) Combustion duration and ITE

Fig. 8. Cylinder pressure and apparent heat release rate (AHRR) under the conditions of different ammonia injection timing.

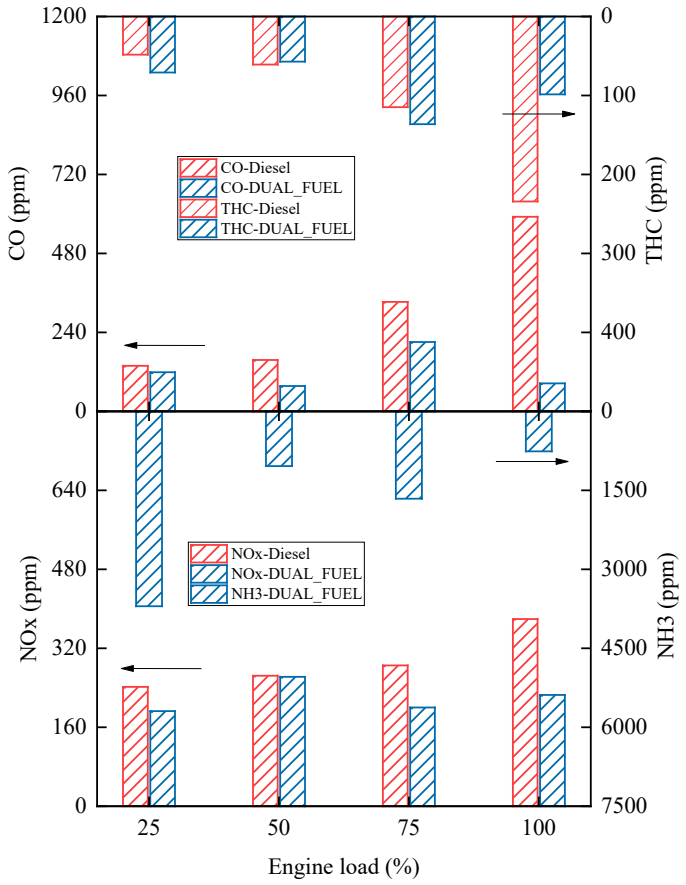
通过调节氨燃料的喷射正时来控制氨燃料的预混合燃烧和扩散燃烧比例，实现液氨分层预混合燃烧和扩散燃烧。

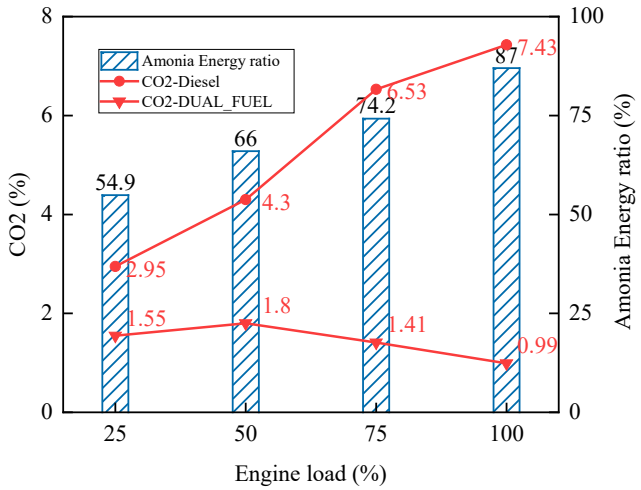
Stratified premixed combustion and diffusion combustion can be achieved respectively by adjusting ammonia injection timing.

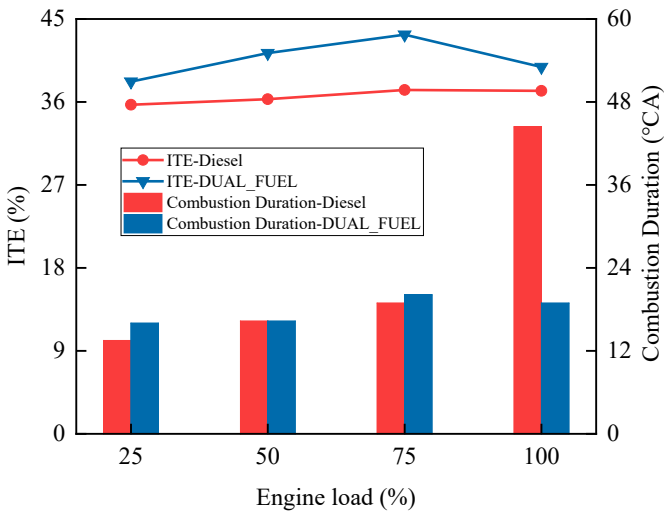
Zhang, Z., et al., Performance characteristics of a two-stroke low speed engine applying ammonia/diesel dual direct injection strategy. Fuel, 2023. 332: p. 126086.

双直喷氨发动机研究 (Ammonia/diesel dual-direct-injection two-stroke engine)

原理样机负荷特性（Constant speed characteristics）





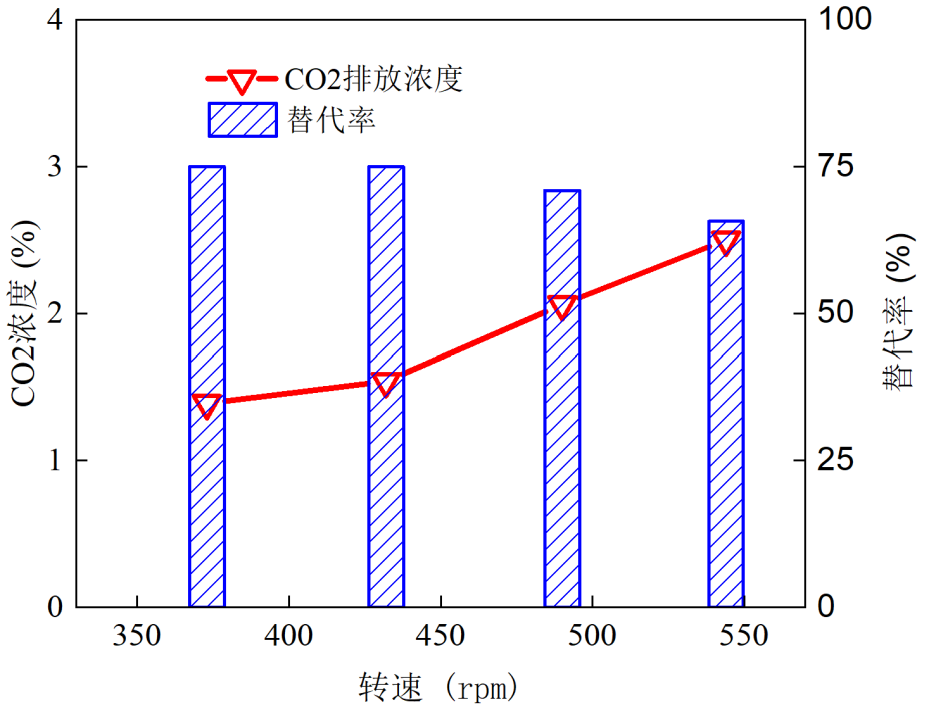


双直喷模式相比柴油模式，热效率更高并且能够显著降低二氧化碳排放，但需要控制未燃氨排放。

Compared with diesel mode, dual-direct-injection mode has higher thermal efficiency and dramatical CO2 emission reduction, even though the ammonia emission need to be controlled.

双直喷氨发动机研究 (Ammonia/diesel dual-direct-injection two-stroke engine)

70%负荷下的速度特性（Fixed rack characteristics ）

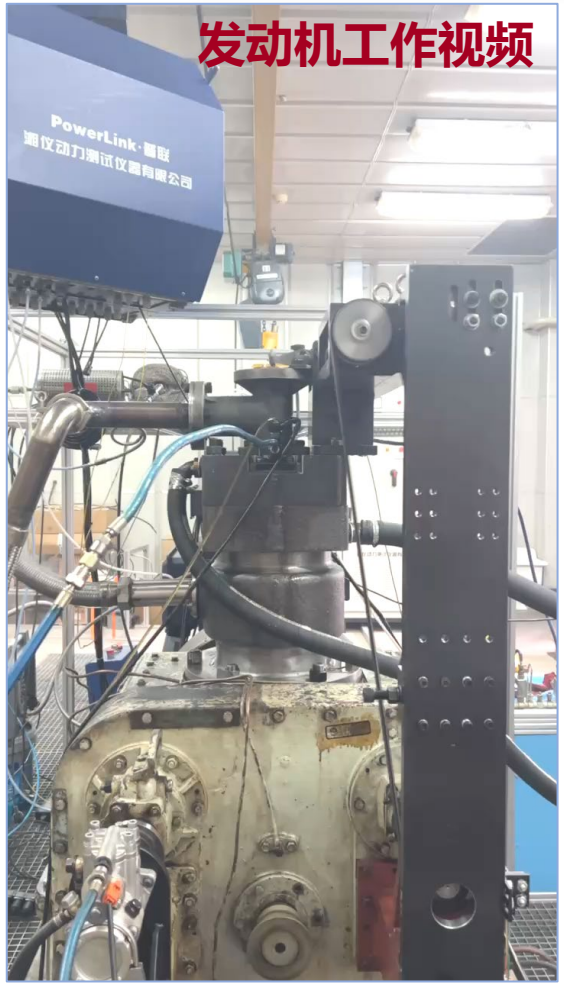


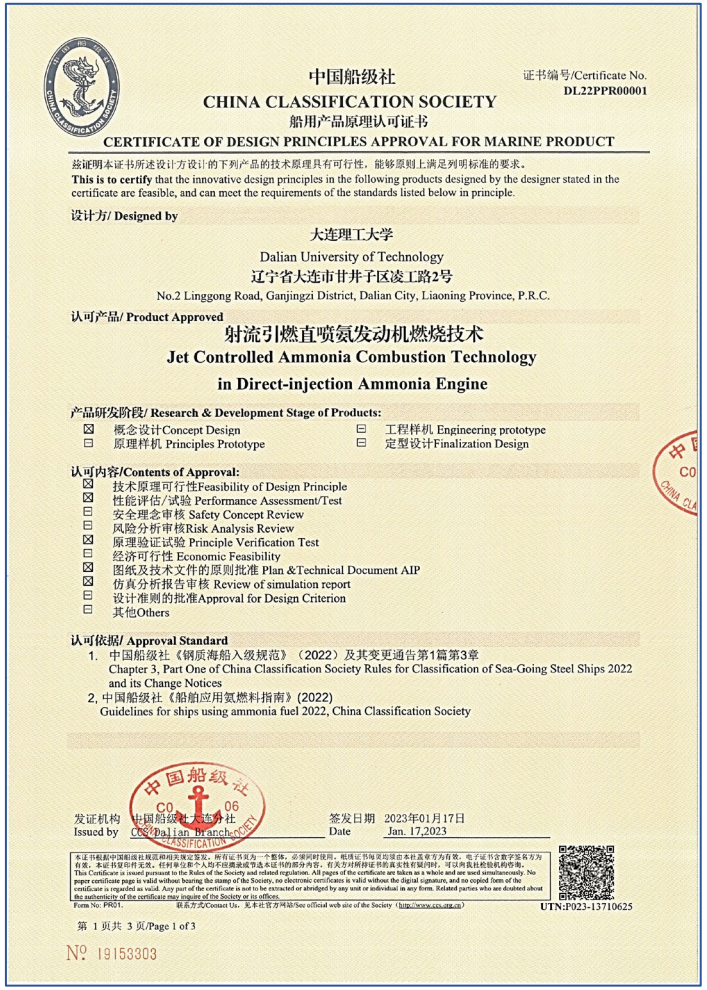
保证相应氨喷射速率的前提下，可实现更宽泛的转速范围。

Higher operation speed can be achieved if guaranteeing the corresponding ammonia injection rate.

双直喷氨发动机研究 (Ammonia/diesel dual-direct-injection two-stroke engine)

首台液氨/柴油双直喷二冲程原理样机
（The first Ammonia/diesel dual-direct-injection two-stroke protype engine）





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认可产品/ Product Approved
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Jet Controlled Ammonia Combustion Technology
in Direct-injection Ammonia Engine

产品研发阶段/ Research & Development Stage of Products:
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☐ 原理样机 Principles Prototype ☐ 定型设计Finalization Design

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☐ 风险分析审核Risk Analysis Review
☒ 原理验证试验 Principle Verification Test
☐ 经济可行性 Economic Feasibility
☒ 图纸及技术文件的原则批准 Plan &Technical Document AIP
☒ 仿真分析报告审核 Review of simulation report
☐ 设计准则的批准Approval for Design Criterion
☐ 其他Others

认可依据/ Approval Standard
1. 中国船级社《钢质海船入级规范》（2022）及其变更通告第1篇第3章
Chapter 3, Part One of China Classification Society Rules for Classification of Sea-Going Steel Ships 2022 and its Change Notices
2. 中国船级社《船舶应用氨燃料指南》(2022)
Guidelines for ships using ammonia fuel 2022, China Classification Society

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氨替代率达90%
Ammonia substitution rate=90%

各类污染物显著降低
Lower pollutant emissions

动力性能优越
Excellent power performance

热效率更高
Higher thermal efficiency

CCS首份射流引燃直喷氨发动机燃烧技术船用产品原理认可证书

CCS's first certificate of principle approval for combustion technology of "JCAC" — "Jet Controlled Ammonia Combustion Technology in Direct-injection Ammonia Engine"

目录

CONTENTS

结论(Conclusions)

1.甲醇扩散燃烧比柴油扩散燃烧更快，柴油甲醇扩散燃烧模式具有明显的高效清洁燃烧特征。

The diffusion combustion rate of the DMDC mode is higher than that of the CDC mode, and the DMDC mode has advance in high efficient and clean combustion.

2.液氨直喷扩散燃烧能够显著提高氨的燃烧速度和燃烧效率。

Liquid phase ammonia direct-injection diffusion combustion can improve the combustion rate and efficiency dramatically.

大连理工大学
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Thanks !