大连理工大学
DALIAN UNIVERSITY OF TECHNOLOGY

柴油机预混合压燃的发展与研究

Development and research on premixed charge compression ignition of diesel engine

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Research background: high-efficiency and clean combustion

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Thermal efficiency: diesel engine ＞ gasoline engine

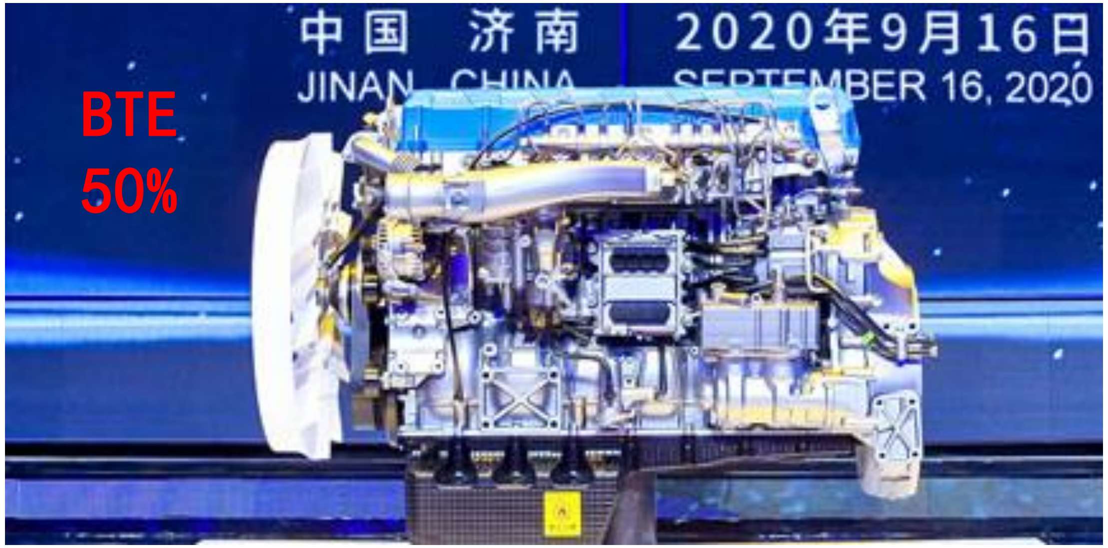
- 高压缩比 Higher compression ratio
- 不存在节流损失 No throttling loss

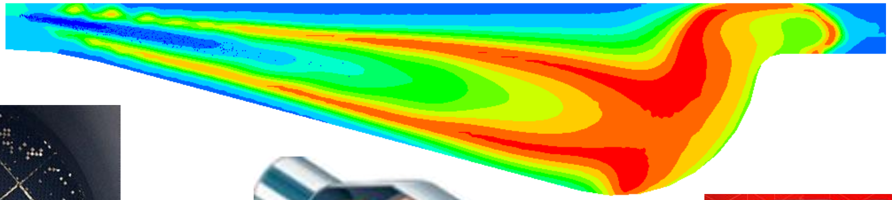
2.柴油机NOx和Soot排放高
NOx and Soot: diesel engine ＞ gasoline engine

- 局部燃烧高温 Local high-temperature
- 局部富燃区域 Local fuel rich region

3.柴油机尾气后处理装置
After-treatment devices of diesel engine

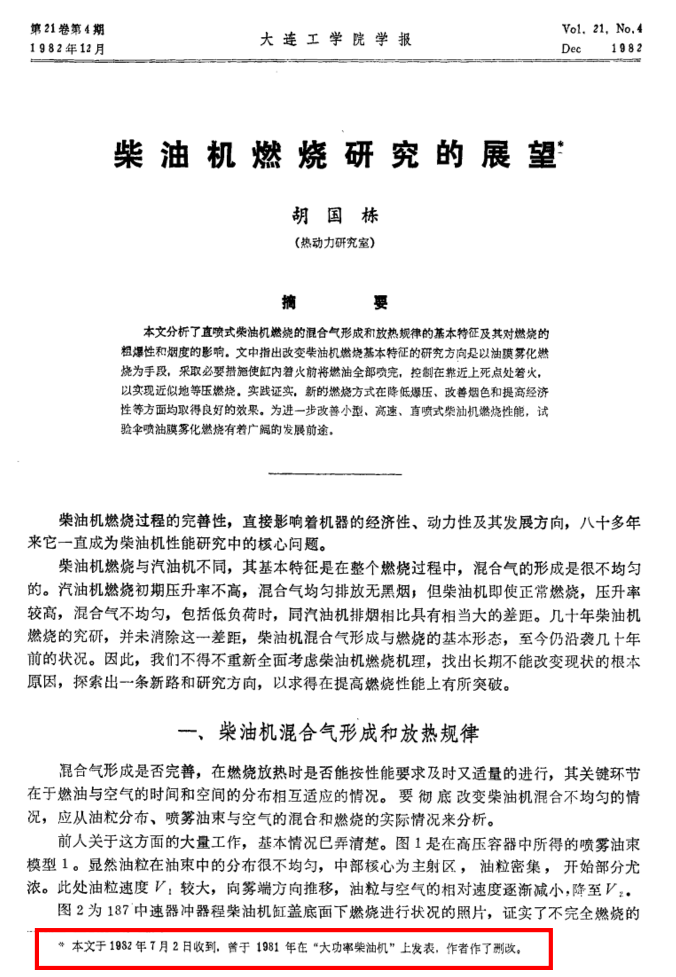
DPF：定期清理积碳积灰 Periodic cleaning
LNT：贵金属, 效率低 Precious metal & Low efficiency
SCR：需还原剂氨, 增加成本 Ammonia additional cost





研究背景：柴油机热预混合燃烧

Research background: HPDC, Hot Premix of Diesel Combustion



第21卷第4期 大连工学院学报 Vol. 21, No.4
1982年12月 Dec 1982

柴油机燃烧研究的展望*

胡国栋
（热动力研究室）

摘要

本文分析了直喷式柴油机燃烧的混合气形成和放热规律的基本特征及其对燃烧的粗爆性和烟度的影响。文中指出改变柴油机燃烧基本特征的研究方向是以油膜雾化燃烧为手段，采取必要措施使缸内着火前将燃油全部喷完，控制在靠近上死点处着火，以实现近似地等压燃烧。实践证实，新的燃烧方式在降低爆压、改善烟色和提高经济性等方面均取得良好的效果。为进一步改善小型、高速、直喷式柴油机燃烧性能，试验伞喷油膜雾化燃烧有着广阔的发展前途。

柴油机燃烧过程的完善性，直接影响着机器的经济性、动力性及其发展方向，八十多年来它一直成为柴油机性能研究中的核心问题。

柴油机燃烧与汽油机不同，其基本特征是在整个燃烧过程中，混合气的形成是很不均匀的。汽油机燃烧初期压升率不高，混合气均匀排放无黑烟；但柴油机即使正常燃烧，压升率较高，混合气不均匀，包括低负荷时，同汽油机排烟相比具有相当大的差距。几十年柴油机燃烧的究研，并未消除这一差距，柴油机混合气形成与燃烧的基本形态，至今仍沿袭几十年前的状况。因此，我们不得不重新全面考虑柴油机燃烧机理，找出长期不能改变现状的根本原因，探索出一条新路和研究方向，以求得在提高燃烧性能上有所突破。

一、柴油机混合气形成和放热规律

混合气形成是否完善，在燃烧放热时是否能按性能要求及时又适量的进行，其关键环节在于燃油与空气的时间和空间的分布相互适应的情况。要彻底改变柴油机混合不均匀的情况，应从油粒分布、喷雾油束与空气的混合和燃烧的实际情况来分析。

前人关于这方面的大量工作，基本情况已弄清楚。图1是在高压容器中所得的喷雾油束模型1。显然油粒在油束中的分布很不均匀，中部核心为主射区，油粒密集，开始部分尤浓。此处油粒速度 V_1 较大，向雾端方向推移，油粒与空气的相对速度逐渐减小，降至 V_2。

图2为187中速器冲器程柴油机缸盖底面下燃烧进行状况的照片，证实了不完全燃烧的

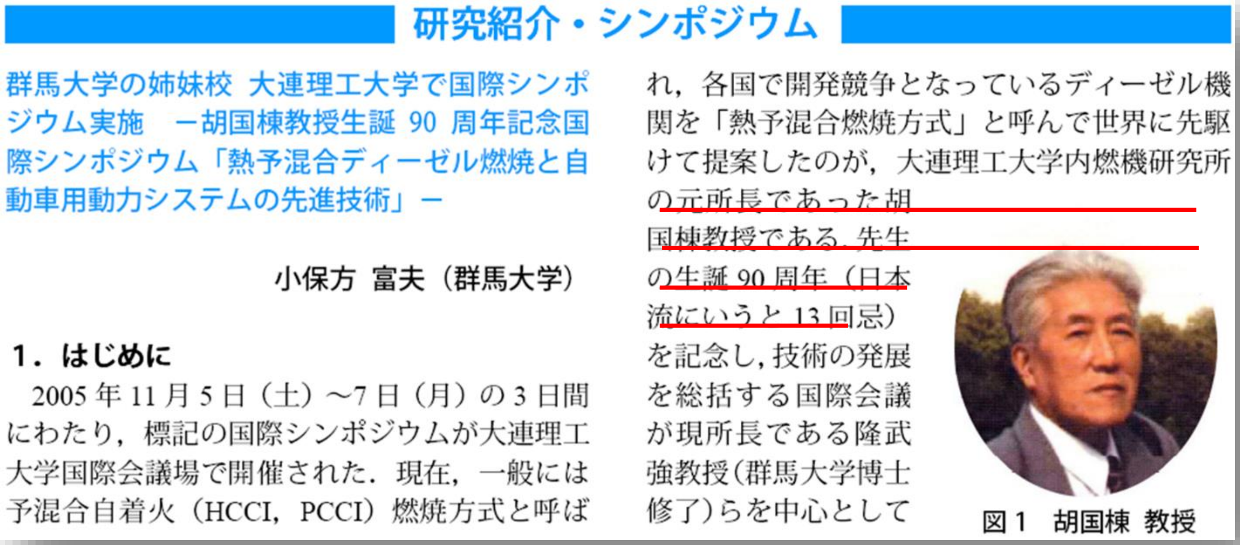
* 本文于1982年7月2日收到，曾于1981年在"大功率柴油机"上发表，作者作了删改。

胡国栋. 柴油机燃烧研究的展望 [J]. 大连工学院学报, 1982 (04):71-80.

1981年提出柴油机热预混合燃烧的概念，包括：

HPDC(Hot Premixed Diesel Combustion) was proposed by Hu in 1981

- **缸内着火前将燃油全部喷完，采用伞喷油嘴制备油气混合气；**
  Preparation of pre-mixture with conical injector
- **柴油机在混合气形成和放热规律方面汽油机化；**
  Gasoline-engine-like mixture formation and heat release pattern



研究紹介・シンポジウム

群馬大学の姉妹校 大連理工大学で国際シンポジウム実施 ―胡国棟教授生誕 90 周年記念国際シンポジウム「熱予混合ディーゼル燃焼と自動車用動力システムの先進技術」―

小保方 富夫（群馬大学）

1．はじめに

2005 年 11 月 5 日（土）～7 日（月）の 3 日間にわたり，標記の国際シンポジウムが大連理工大学国際会議場で開催された．現在，一般には予混合自着火（HCCI，PCCI）燃焼方式と呼ばれ，各国で開発競争となっているディーゼル機関を「熱予混合燃焼方式」と呼んで世界に先駆けて提案したのが，大連理工大学内燃機研究所の元所長であった胡国棟教授である．先生の生誕 90 周年（日本流にいうと 13 回忌）を記念し，技術の発展を総括する国際会議が現所長である隆武強教授（群馬大学博士修了）らを中心として

図 1 胡国棟 教授

该燃烧模式以预混合充量压缩着火被广泛熟知。

HPDC was widely known as PCCI (Premixed Charge Compression Ignition) mode.

研究背景：柴油机预混合压燃模式

Research background: premixed charge compression ignition of diesel engine

柴油机预混合压燃模式的实现方法 Realization of PCCI

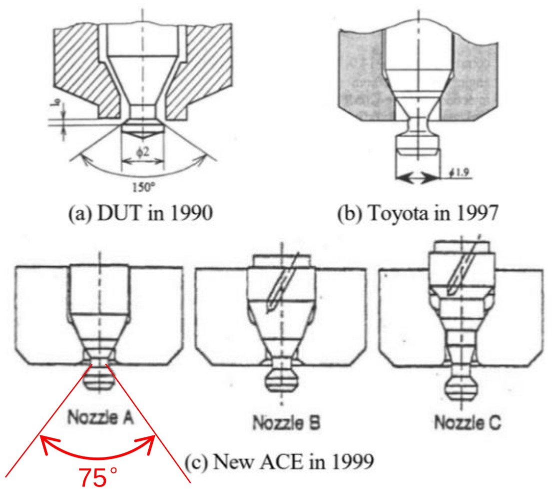


图1 伞喷油嘴结构 Conical spray nozzle

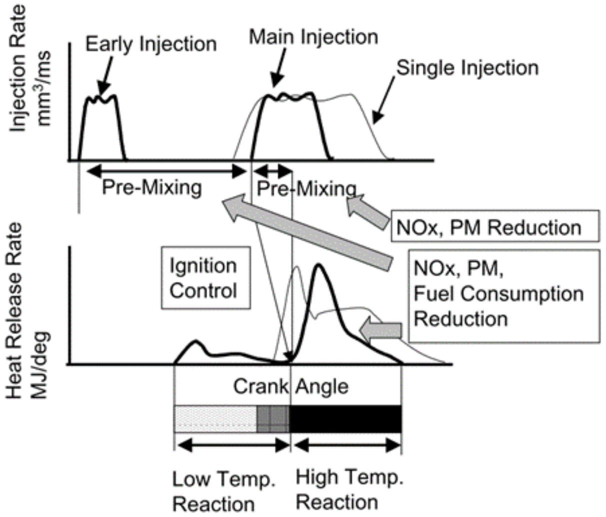


图2 丰田公司 UNIBUS

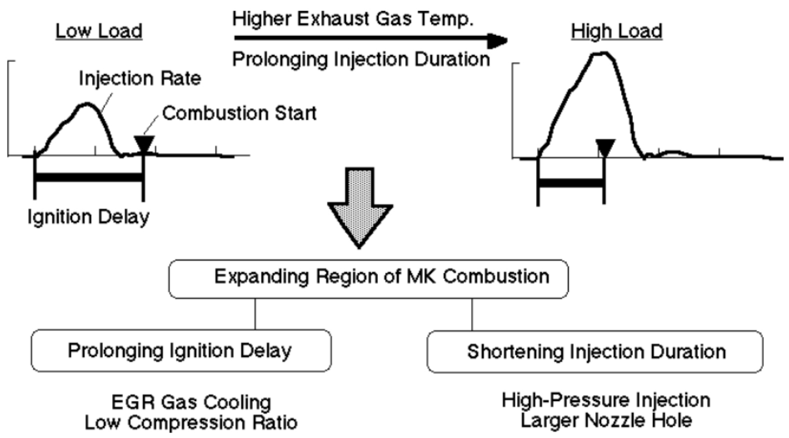
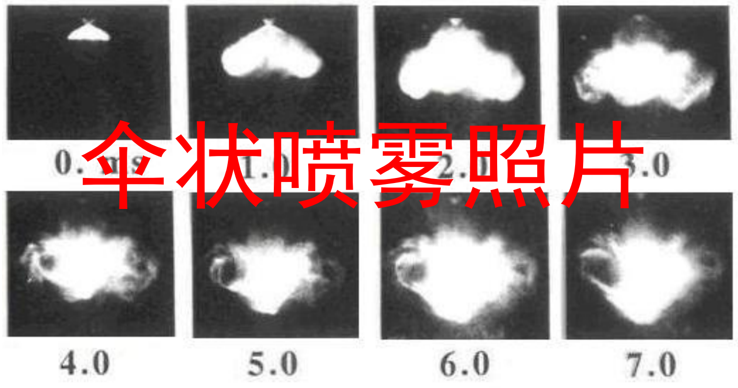


图3 日产 MK



- 改进喷雾制备油气混合气 Improving atomization
- 缸内早喷、多次喷射 Early injection, multi-injection
- 缸内晚喷，延长滞燃期 Late injection with longer ignition delay

预混合均匀性和着火相位可控性的矛盾

Trade off between homogeneity & Ignition timing controllability

1.Yanagihara, JSME International Journal, 1997; 2.Akagawa, SAE, 1999-01-0183; 3.Hasegawa, SAE, 2003-01-0745; 4.Kimure, SAE, 2001-01-0200

高扰动喷嘴：柴油预混合气制备
High Disturbance (HD) nozzle: preparation of diesel pre-mixture

1.燃油喷射系统发展趋势
Development tendency of fuel injection system

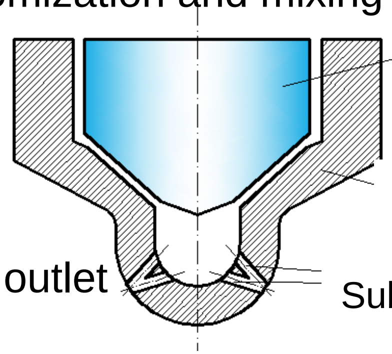
- 高压、超高压喷射 Increased injection pressure
- 小/微孔径 Downsized hole diameter
- 时间/空间分割 Time and space division

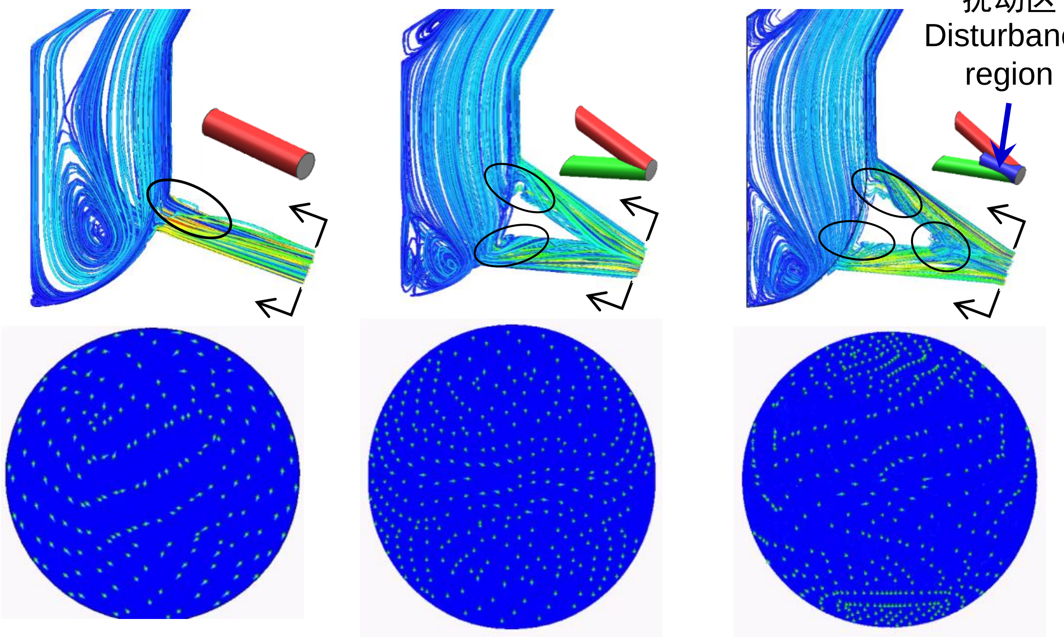
2.设计思想
Design concept

- 增加内流扰动 Increased internal flow disturbance
- 促进雾化和混合 Improved atomization and mixing

3.几何结构
Geometric construction

- 2个子喷孔汇聚到1个出口
  Two sub-holes converge at one outlet
- 设置扰动区
  Disturbance region





喷孔内的流线
Stream line in the HD nozzle

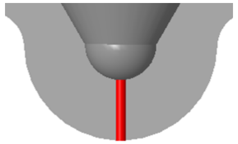
高扰动喷嘴结构造成了更加复杂的内流扰动
More complex internal flow disturbance is produced by the high disturbance nozzle structure

高扰动喷嘴：柴油预混合气制备

High disturbance nozzle: preparation of diesel pre-mixture

柴油喷雾可视化试验Visualization experiment of diesel spray

单孔



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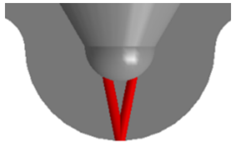
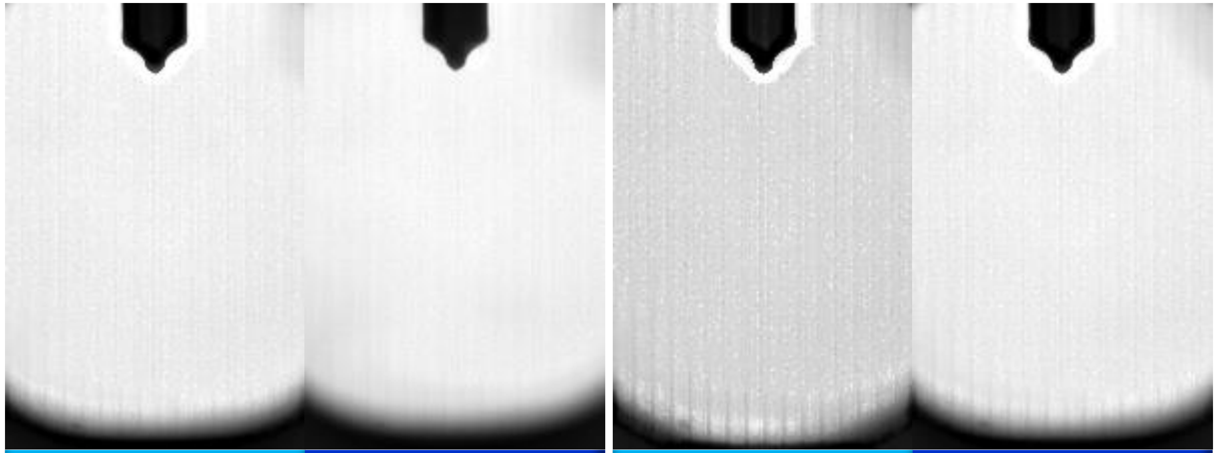
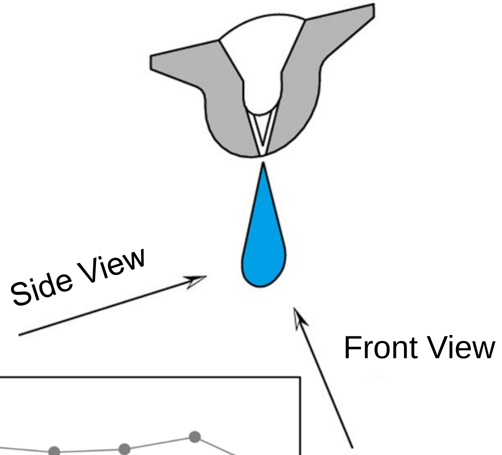
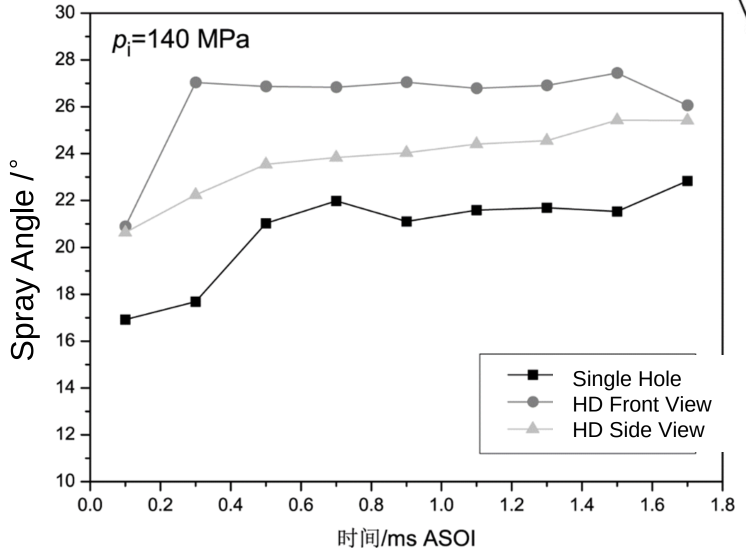




侧向 Side view	正向 Front View	侧向 Side view	正向 Front View





射流控制压缩着火（JCCI）模式

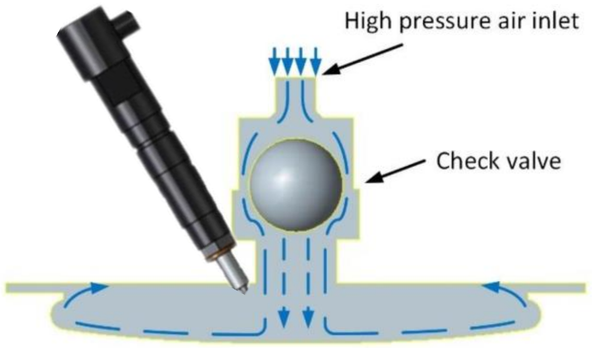
JCCI: Jet Controlled Compression Ignition

1. 在进气冲程或压缩冲程早期，制备灵活的稀薄预混合气。
The flexible lean pre-mixture is prepared during the intake or compression stroke.

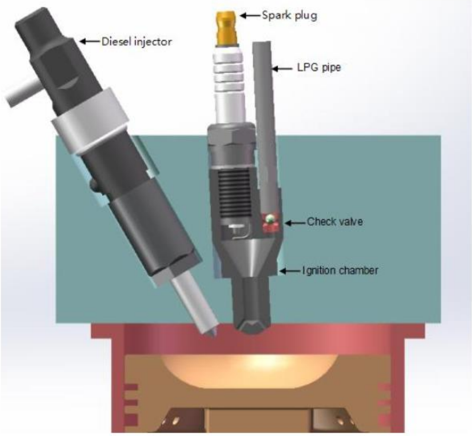
2. 控制有效压缩比等条件，使混合气处于接近自燃的临界状态。
The unburned pre-mixture is controlled in the critical state of auto-ignition.

3. 在压缩上止点附近，通过**射流**触发缸内的预混合气自燃。
The pre-mixture ignition is induced by **Jet** near TDC.

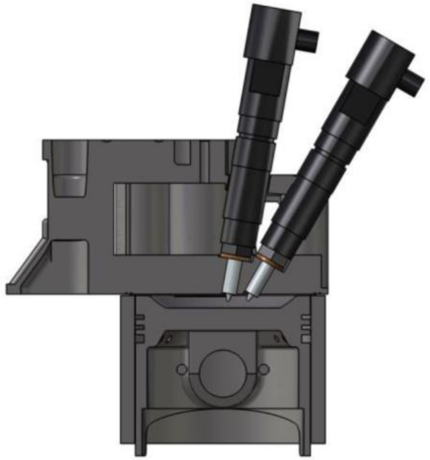
4. 通过控制射流正时，主动控制预混合气的着火相位。
The ignition timing is actively controlled by the jet timing.



高压空气射流
High-pressure air jet



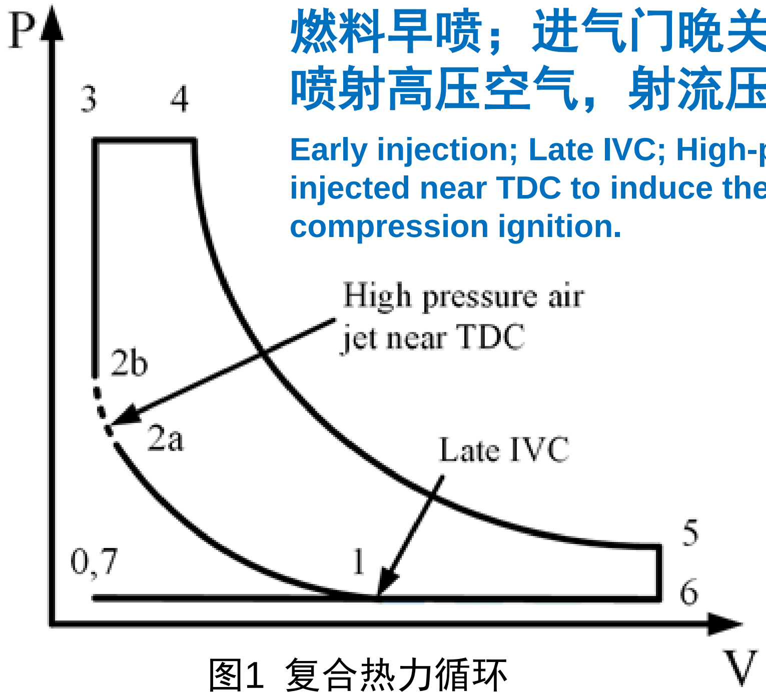
高温火焰射流
High temperature flame jet



柴油射流
Diesel fuel jet

JCCI：高压空气射流

JCCI: High-pressure air jet



燃料早喷；进气门晚关；上止点附近喷射高压空气，射流压燃预混合气。

Early injection; Late IVC; High-pressure air is injected near TDC to induce the pre-mixture compression ignition.

图1 复合热力循环
Fig.1 Compound thermodynamic cycle

- 低压缩比 Low compression ratio
- 高压升比 High pressure-rise ratio
- 高膨胀比 High expansion ratio

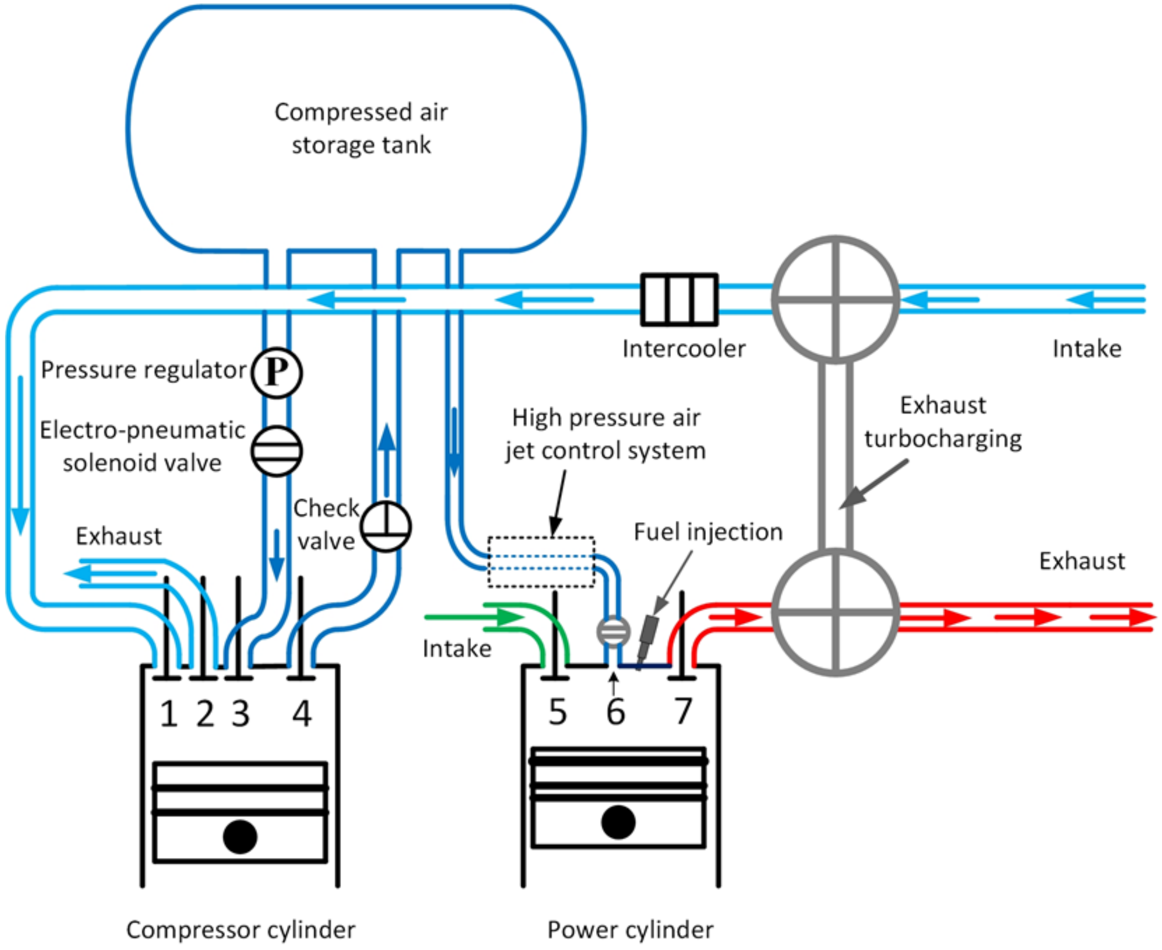
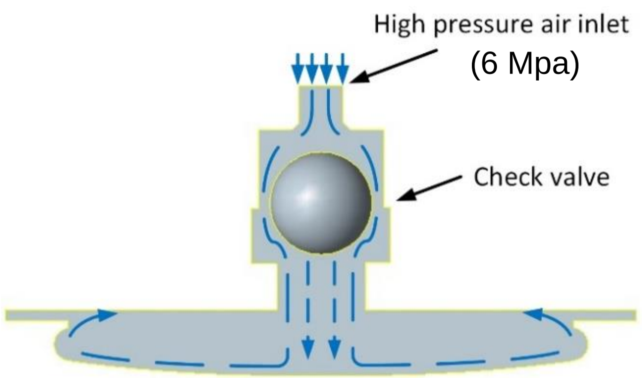
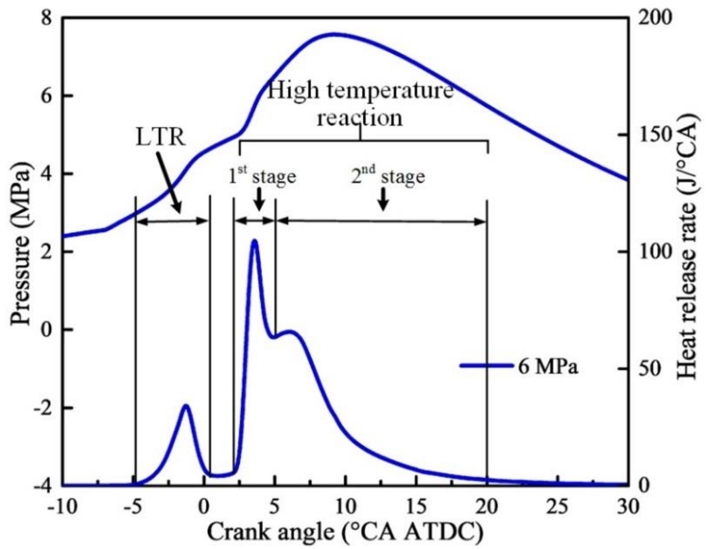


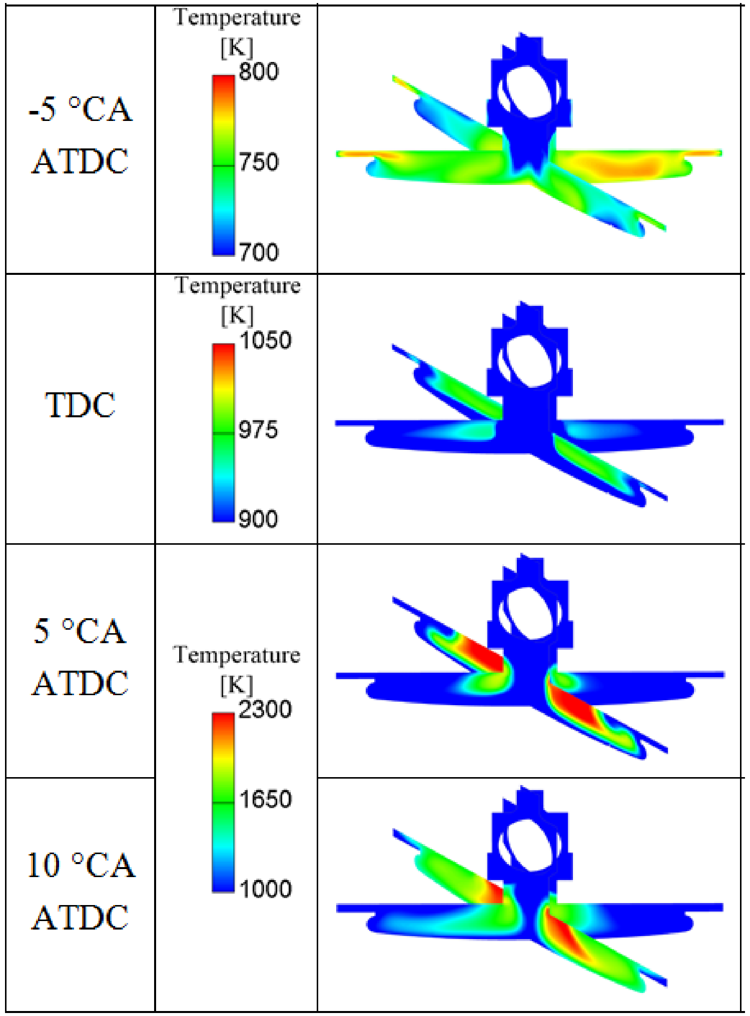
图2 复合发动机
Fig.2 Compound engine

JCCI：高压空气射流

JCCI: High-pressure air jet







- 放热规律：明显的低温反应和两阶段高温反应。

  One low-temperature reaction and two-stage high-temperature reaction

- 第一阶段高温反应：由高压气体射流压缩引起。

  First stage high-temperature reaction is induced by the compression of high-pressure air

- 第二阶段高温反应：受混合过程影响。

  Second stage high-temperature reaction is influenced by the mixing process

JCCI：高压空气射流
JCCI: High-pressure air jet

高压空气射流参数
High-pressure air jet parameters

Parameters	Values
Jet temperature (K)	500
Jet pressure (MPa)	7
Start of jet (°CA ATDC)	-12, -9, -6, -3 and 0
Jet duration (°CA)	10

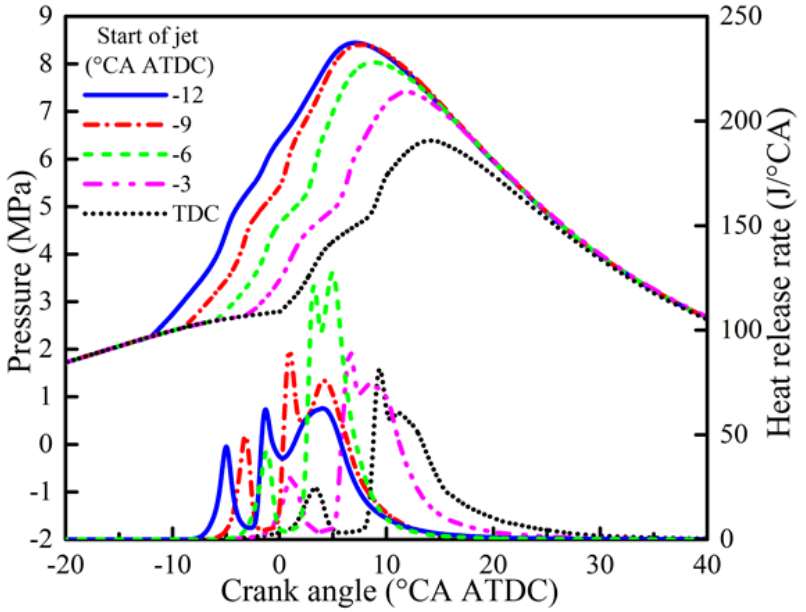


图1 缸压与放热率随射流正时变化

Fig.1 Effects of SOJ timing on in-cylinder pressure and heat release rate

- **随高压空气射流正时的推迟，SOC和CA50均逐渐延后，表明了高压气体射流对相位的直接控制效果。**

The results reveal the direct control of high-pressure air jet on the SOC and CA50.

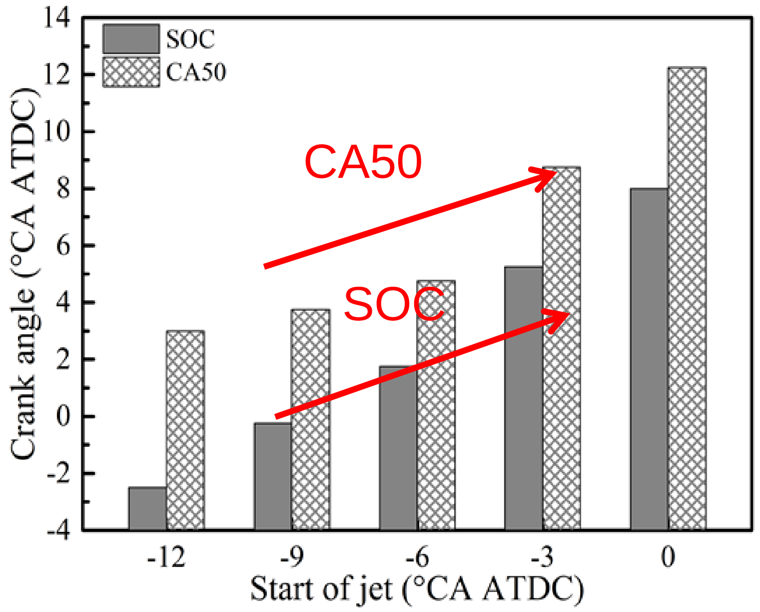
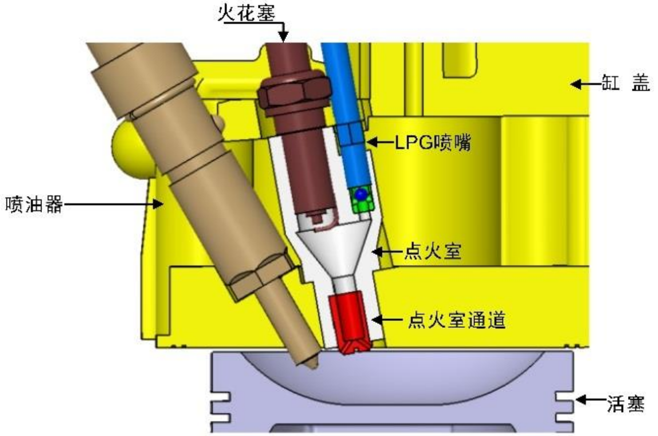


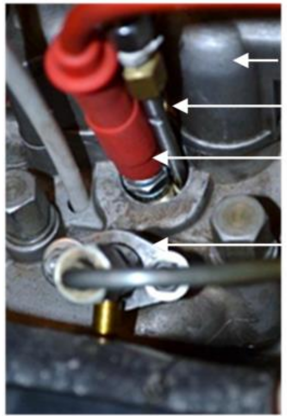
图2 射流正时对着火与燃烧相位的影响

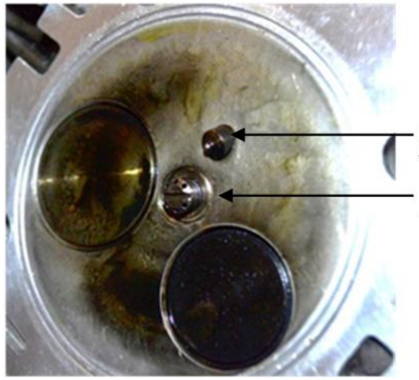
Fig.2 Effects of SOJ timing on SOC and CA50

JCCI：高温火焰射流（单缸机试验）

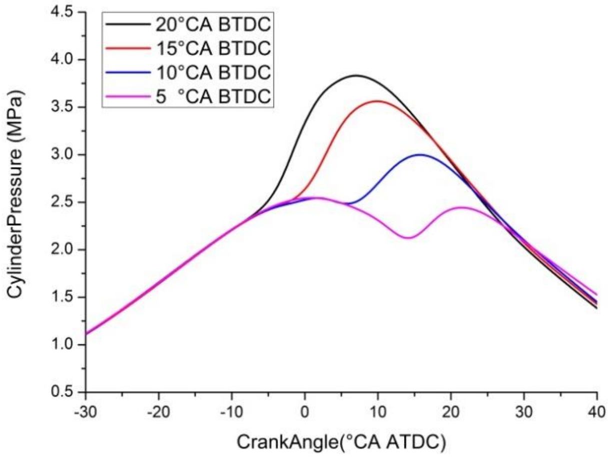
JCCI: High-temperature flame jet (Test on SCTE (Single Cylinder Test Engine))

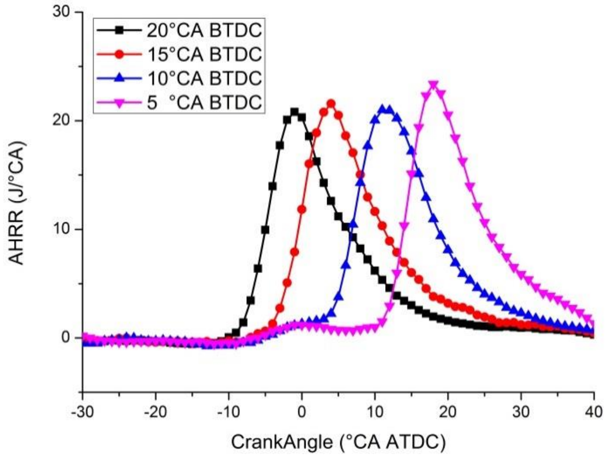


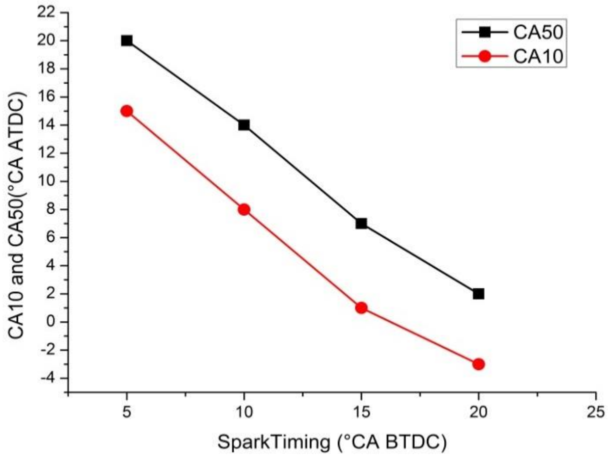




高温火焰JCCI发动机试验系统 Experimental system of high-temperature flame JCCI





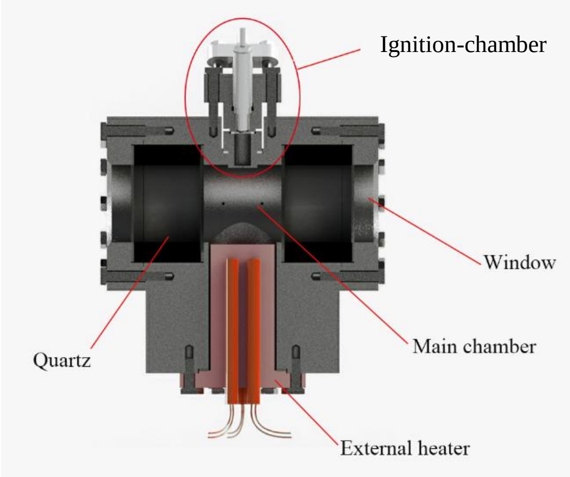


点火正时对缸压、放热率、CA10和CA50的影响

Effects of ignition timing on in-cylinder pressure, HRR, CA10 and CA50

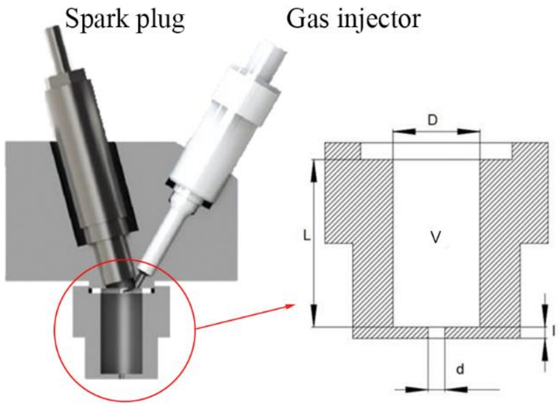
JCCI：高温火焰射流（定容弹可视化试验）

JCCI: High-temperature flame jet (Visualization on CVB (Constant Volume Bomb))



点火室火焰射流可视化试验平台

Visualization experiment platform

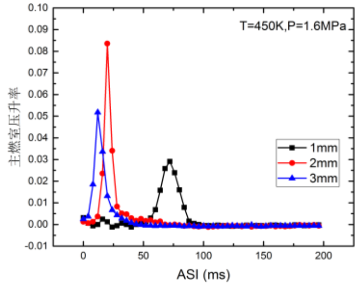


Ignition Chamber (IC)　Lower part

1.点火室喷孔直径对射流引燃特性的影响（T=450K, P=1.6MPa, Φ=1）

Effects of ignition-chamber orifice diameter on the jet ignition characteristics

1mm　2mm　3mm

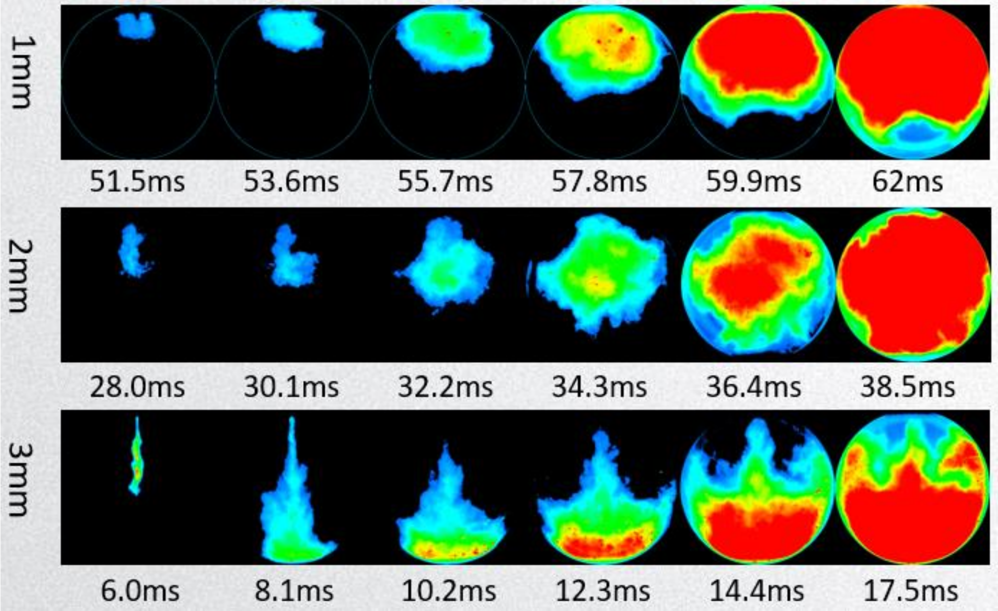


主燃室压升率

MPRR in main-chamber

2.不同孔径点火室射流自然发光影像（T=300K,P=1MPa,Φ=1）

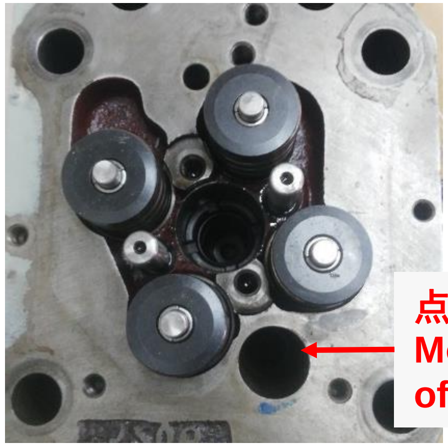
Jet natural luminescence image of different ignition-chamber orifice diameter

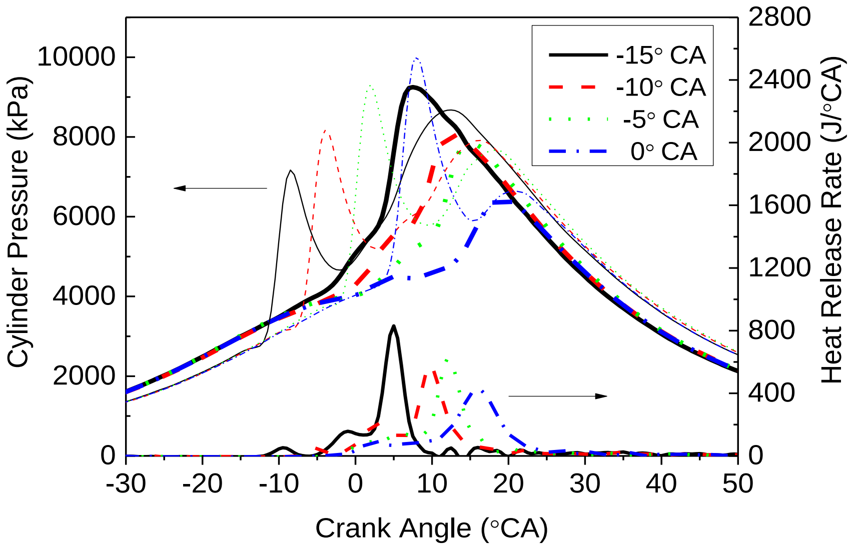


JCCI：高温火焰射流（多缸机样机）

JCCI: High-temperature flame jet (Multi-cylinder proto-type engine)

Parameter	Value
Cylinder number	8
Bore (mm)	132
Compression ratio	12:1
Rated power/speed (kW/rpm)	300 / 1500

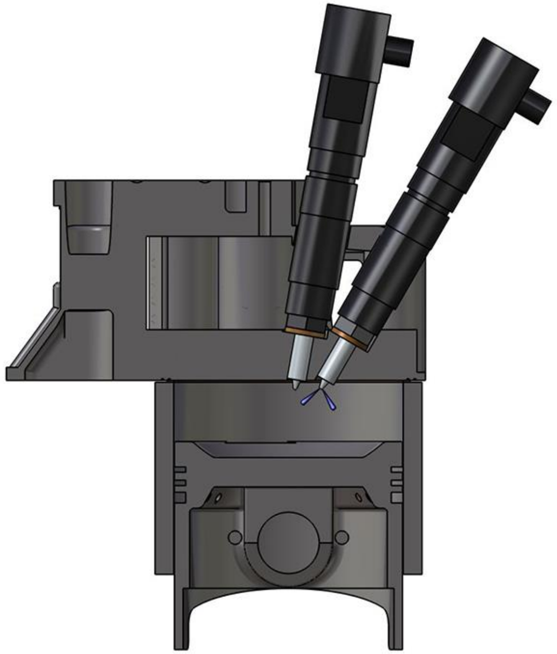




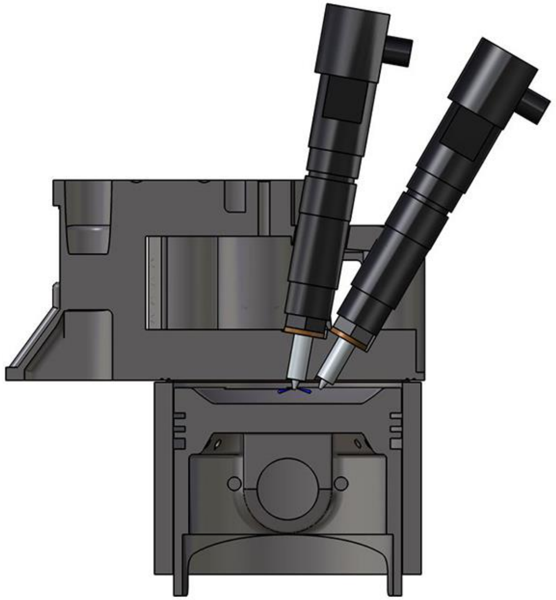
不同点火正时下JCCI工作过程的缸压和放热率（ Tin= 70℃）
Effects of spark timing on in-cylinder pressure and HRR for JCCI mode

JCCI：柴油射流
JCCI: Diesel fuel jet

柴、汽油机“混合气形成、燃烧方式及使用燃料”的统一
Unity of mixture formation, ignition mode and fuels between diesel and gasoline engine



-60°CA ATDC



-17°CA ATDC

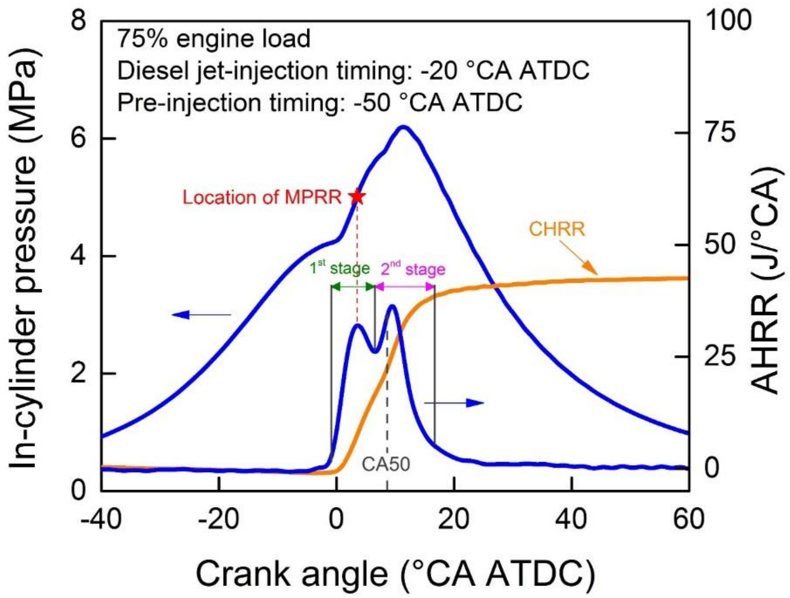
柴油JCCI喷油系统布置示意图
Schematic diagram of dual–direct injection system for diesel JCCI

燃烧室形状对比图
Comparisons of stock and modified pistons

Main engine parameters	
Bore*stroke (mm*mm)	86*72
Displacement (L)	0.418
Geometrical compression ratio	19/15.5:1
Rated power / speed (kW/rpm)	5.68 / 3000

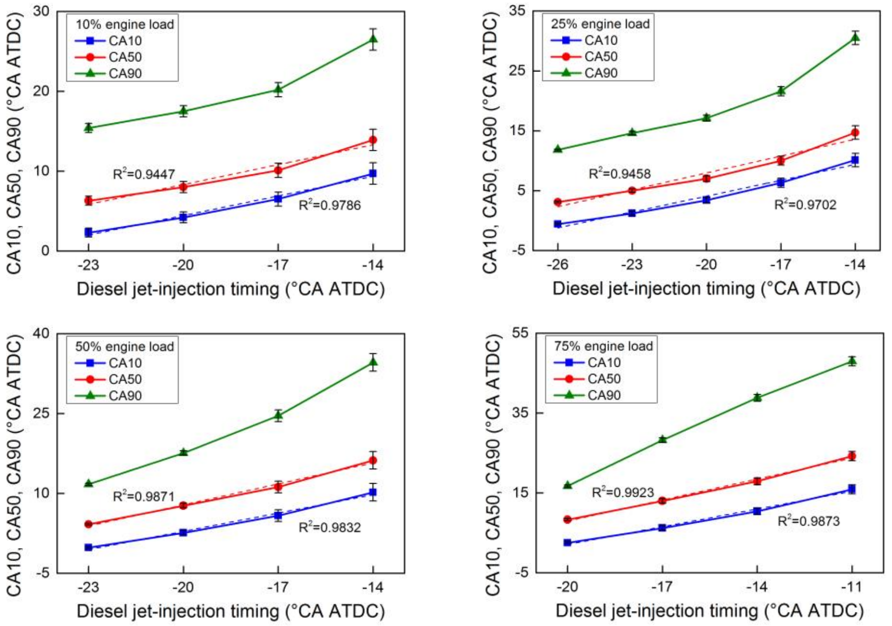
JCCI：柴油射流

JCCI: Diesel fuel jet



柴油射流JCCI的缸压与放热率

In-cylinder pressure and HRR of diesel jet JCCI



柴油射流正时对CA10、CA50和CA90的影响

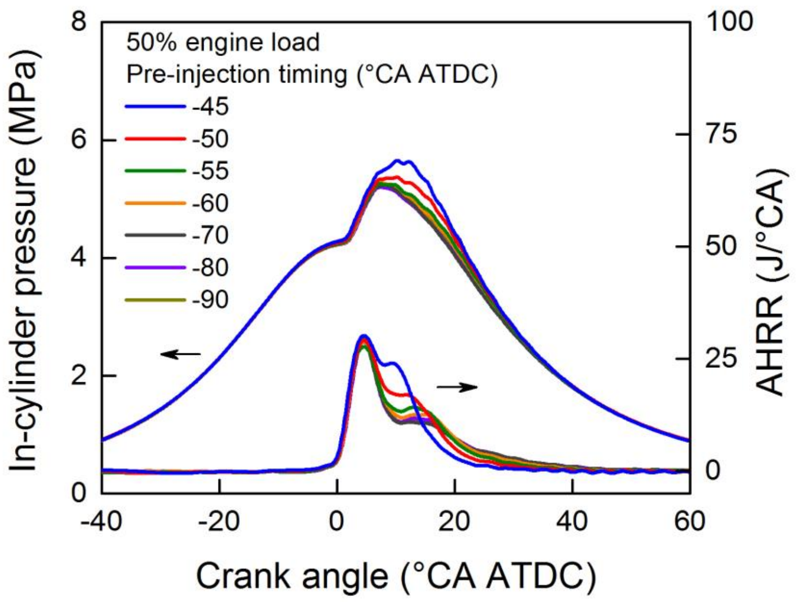
Effects of diesel jet-injection timing on CA10, CA50 and CA90

- **柴油JCCI燃烧分为两个阶段：柴油射流压缩自燃阶段和预混合气燃烧阶段。**
  Two-stage combustion process: jet fuel spontaneous combustion stage and pre-mixture combustion stage
- **在四个负荷条件下，CA10和CA50均与柴油射流正时成较好的线性关系。**
  Both CA10 and CA50 are linearly correlated with jet-injection timing

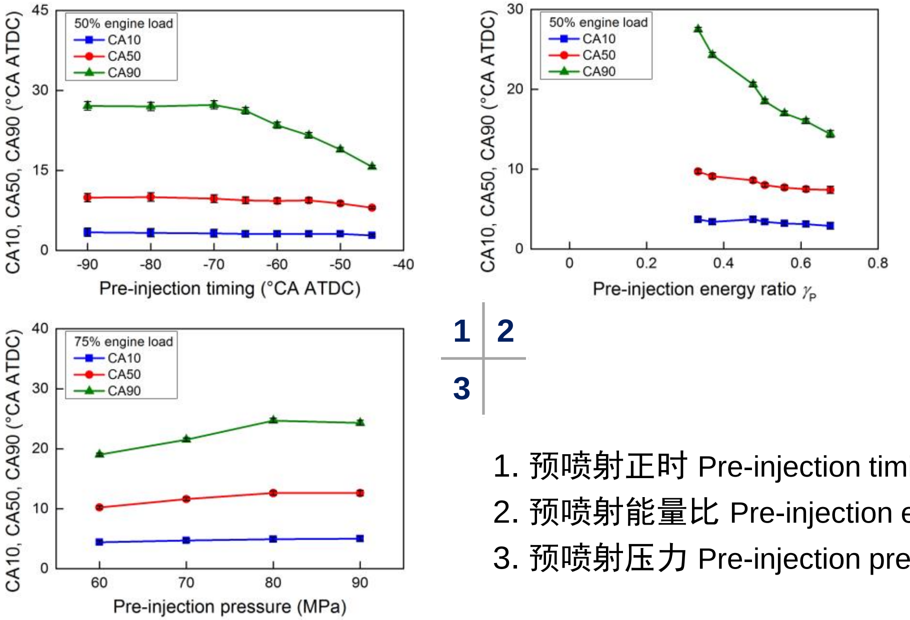
柴油射流可以有效控制预混合气着火相位

Ignition timing and combustion phasing could be controlled by the diesel jet-injection timing effectively

JCCI：柴油射流
JCCI: Diesel fuel jet



预喷射正时对缸压与放热率的影响
Effects of pre-injection timing on in-cylinder pressure and HRR



1. 预喷射正时 Pre-injection timing
2. 预喷射能量比 Pre-injection energy ratio
3. 预喷射压力 Pre-injection pressure

预喷射参数对CA10、CA50和CA90的影响
Effects of pre-injection parameters on CA10, CA50 and CA90

- **预喷射正时对柴油JCCI燃烧的影响存在敏感区间。**
  There is a sensitive region of direct pre-injection timing for the effects on JCCI mode combustion.
- **预喷射参数对柴油JCCI燃烧模式的CA10和CA50影响较小。**
  Pre-injection parameters show few effects on CA10 and CA50 of JCCI mode.

柴油射流对着火相位控制的鲁棒性较强
The diesel fuel jet achieves robust control of the ignition timing and combustion phasing

总结
Conclusion

1. 高扰动喷嘴结构通过内流扰动，改善了柴油的雾化特性，有利于缸内直喷制备柴油预混合气。

High disturbance nozzle has improved the diesel atomization and in-cylinder fuel/air mixing through the internal flow disturbance.

2. 为解决柴油机预混合压燃的着火相位控制难题，提出了射流控制压缩着火（JCCI）的概念，目前根据射流形式的不同分为：高压空气射流，高温火焰射流和柴油燃料射流三种。

JCCI mode was proposed to control the ignition timing of diesel engine premixed compression ignition, including high-pressure air jet, high-temperature flame jet and diesel fuel jet.

3. 三种射流控制压缩着火模式均可以主动有效地控制预混合气的着火相位和燃烧相位，给出了实现柴油机预混合压燃的新途径。

The ignition timing and combustion phasing could be controlled effectively by three types of jet, which introduces new path ways of realizing the premixed compression ignition of diesel engine.

Thank you！