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

基于缸压变动的双燃料发动机燃烧过程评价方法及应用

A novel combustion evaluation method and application based on in-cylinder pressure traces for dual fuel engines

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Presenter: Wang Zhongshu Jilin University

2023年2月

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一、研究意义与背景 Research background and significance

（一）国家战略需求 National strategic needs

习近平总书记在联合国大会

提出二氧化碳排放2030年前碳达峰,2060年碳中和

General Secretary Xi Jinping proposed that carbon dioxide emissions would reach the peak by 2030 and be carbon neutral by 2060 at the United Nations General Assembly.

国务院印发《2030 年前碳达峰行动方案》明确将交通运输绿色低碳行动列为“碳达峰十大行动”之一，并指出“推动运输工具装备低碳转型”为其重点内容。

The State Council issued the Action Plan for Carbon Peak before 2030, which clearly listed the green and low carbon action of transportation as one of the "ten actions for carbon peak", and pointed out that "promoting the low-carbon transformation of transportation means and equipment" as its key content.

一、研究意义与背景 Research background and significance

（二）汽车产销量-喜忧参半 Auto production and sales - Mixed results

我国汽车产销量连续14年保持全球第一

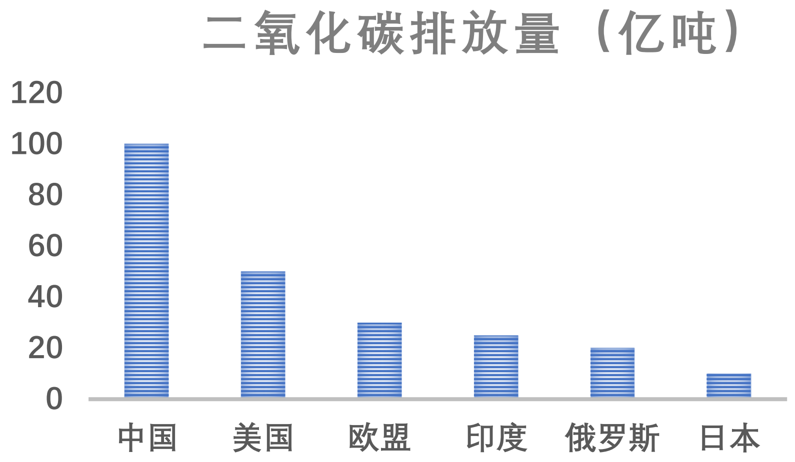
Chinese automobile production and sales have kept the first place in the world for 14 years

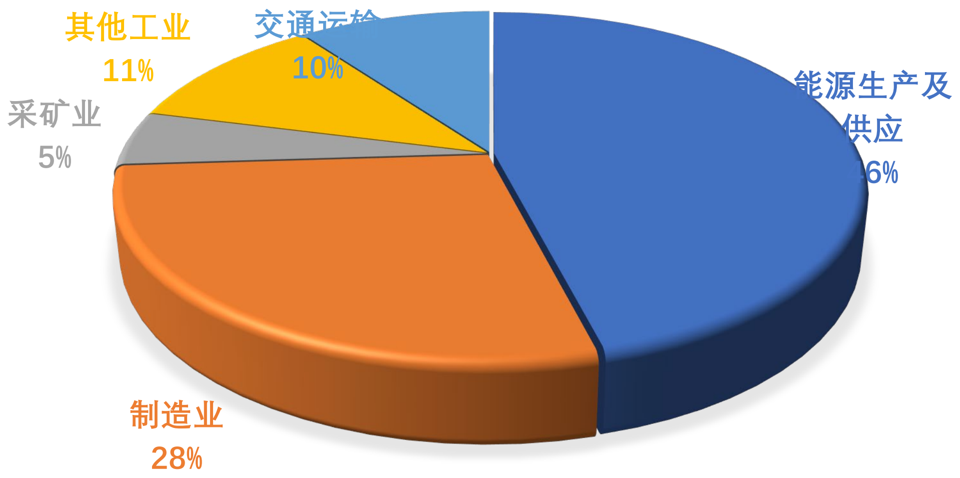
中国汽车工业协会统计数据显示：我国汽车产业在“十四五”开局之年呈现稳中有增的良好发展态势，2022年产销分别完成2702.1万辆和2686.4万辆，连续14年保持全球汽车产销量第一。我国作为世界第一汽车市场大国的地位进一步巩固，正向世界汽车强国迈进。

Statistics from China Association of Automobile Manufacturers show that China's automobile industry has shown a sound development trend of stable growth in the first year of the "14th Five-Year Plan". In 2022, the production and sales of 27.021 million and 26.864 million respectively have been completed, maintaining the first place in global automobile production and sales for 14 consecutive years. China has consolidated its position as the world's largest automobile market and is developing into a world powerful automobile country.

一、研究意义与背景 Research background and significance

（三）科技与产业革命-责任重大 Technology and Industrial Revolution - Great responsibility





据相关统计信息显示：

According to relevant statistics:

- 我国生产消费产生的二氧化碳超过**100亿吨/年**，占全球排放量近**30%**。
- China produces more than 10 billion tons of carbon dioxide per year, accounting for nearly 30 percent of global emissions.
- 我国二氧化碳排放总量中，交通运输业占据**10%**，是全国碳排放**第三大户**，其中汽车占比贡献近**75%**。
- The transport sector accounts for 10% of China's total carbon dioxide emissions and is the third largest carbon emitter in the country, with vehicles accounting for nearly 75%.

一、研究意义与背景 Research background and significance

（四）传统动力的技术革新-调整和机遇 Technological innovation in Traditional Power - Adjustments and Opportunities

内燃机是目前**热效率最高**、**功率密度大**、**应用最为广泛**的动力装置，广泛应用于汽车、船舶、工程机械、农业机械和国防动力各个领域。

Internal combustion engine is the most widely used power device with the highest thermal efficiency, high power density, and widely used in automobile, ship, construction machinery, agricultural machinery and national defense power fields.

传统动力面临的挑战和机遇：

Challenges and opportunities for traditional drivers:

- **"双碳"目标的挑战**，内燃机是主要的CO_2排放来源之一，以内燃机为主的全球交通运输CO_2排放约占24.0%，并持续增长。
- The challenge of the "two-carbon" goal is that the internal combustion engine is one of the major sources of CO2 emissions, and the global transport CO_2 emissions dominated by internal combustion engines account for about 24.0% and continue to grow.
- **能源安全的挑战**，我国石油对外依存度高，2021年我石油对外依存度达到72%，而内燃机消耗了近60%的石油。
- The challenge of energy security is that China has a high dependence on foreign oil, which has reached 72% in 2021, while internal combustion engines consume nearly 60% of the oil.
- **能源动力技术的快速发展为内燃机发展提供了新的机遇**，内燃机本身的优势将在未来的净零碳社会中发挥十分重要的作用。
- The rapid development of energy and power technology provides a new opportunity for the development of internal combustion engine. The advantages of internal combustion engine itself will play a very important role in the net zero carbon society in the future.

一、研究意义与背景 Research background and significance

（五）传统动力的技术革新-汽油机 Technical innovation of traditional power - gasoline engine

20TD发动机满足严格的国6b排放法规，采用高压缩比+米勒循环燃烧等10项核心技术，热效率39%，达到增压直喷发动机顶尖水平，为国内首款量产的米勒循环增压直喷发动机。

The 20TD engine meets the strict national 6b emission regulations, adopts 10 core technologies such as high compression ratio + Miller cycle combustion, and achieves 39% thermal efficiency, reaching the top level of supercharged direct injection engine, making it the first mass-produced Miller cycle supercharged direct injection engine in China.

其采用350bar高压燃油喷射和双流道高响应电控增压技术，助力全新红旗H5实现百公里加速时间7.8s，全面优于竞品车型；采用全铝材料和超低摩擦技术，实现节能低碳；采用小节距齿形静音链和集成式双平衡轴，让全新红旗H5用户真实感受到低振动、高舒适；开发全MAP智能热管理控制技术，实现发动机温度精准控制和高效运行，也标志着红旗总成产品进入智能化时代。

It adopts 350bar high-pressure fuel injection and dual-channel high-response electronic-controlled supercharging technology to help the new Hongqi H5 achieve a 100km acceleration time of 7.8s, which is comprehensively superior to competing models. Adopt all-aluminum material and ultra-low friction technology to realize energy saving and low carbon; Adopt the small pitch toothed mute chain and integrated double balance shaft, so that the new Hongqi H5 users really feel low vibration and high comfort; The full MAP intelligent thermal management control technology is developed to realize accurate control and efficient operation of engine temperature, which also marks the entry of Hongqi Assembly products into the era of intelligence.

一、研究意义与背景 Research background and significance

（五）传统动力的技术革新-柴油机 Technical innovation of traditional power - diesel engine

全球首款本体热效率52.28%柴油机发布：

Release of the world's first bulk thermal efficiency 52.28% diesel engine:

潍柴在2020年柴油机本体热效率突破**50.23%**、2022年1月突破**51.09%**的基础上，2022年11月再一次创造了**52.28%**的全球新纪录，连续三次走向世界行业巅峰。

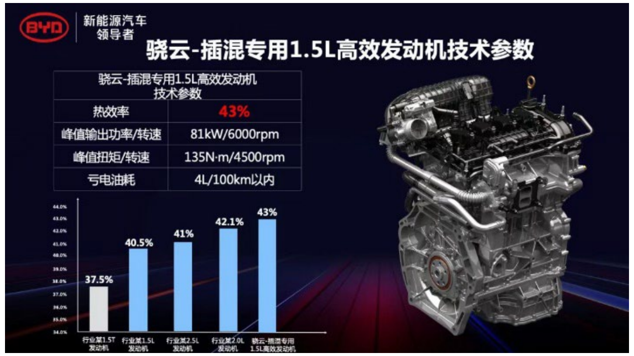
On the basis of the diesel engine bulk thermal efficiency breaking 50.23% in 2020 and 51.09% in January 2022, Weichai once again created a new global record of 52.28% in November 2022, reaching the world industry peak for three consecutive times.

天然气发动机本体热效率全球首次突破**54.16%**，是对内燃机行业的一次革命性颠覆，天然气发动机热效率首次超越柴油机，成为了热效率最高的热力机械。

The thermal efficiency of natural gas engine has broken through 54.16% for the first time in the world, which is a revolutionary subversion of the internal combustion engine industry. The thermal efficiency of natural gas engine has surpassed the diesel engine for the first time and become the thermal machinery with the highest thermal efficiency.

一、研究意义与背景 Research background and significance

（五）传统动力的技术革新-混动专用发动机 Technical innovation of traditional power - special hybrid engine



DM-i超级混动驱动系统包括三大核心部件：

The DM-i Super hybrid drive system consists of three core components:

骁云-插混专用1.5L高效发动机具有全球领先的热效率43.04%，15.5：1超高压缩比，采用阿特金森循环、冷却EGR、分体冷却、超低摩擦、无轮系设计的行业领先技术。

The Snapcloud-Plug-in special 1.5L high efficiency engine has the world's leading thermal efficiency of 43.04%, 15.5:1 ultra-high compression ratio, and adopts the industry leading technology of Atkinson cycle, cooling EGR, split cooling, ultra-low friction and no wheel train design.

EHS电混系统的电机最高转速达16000rpm；扁线电机，最高效率达到97.5%，高效区占比高达90.3%（高效区指效率超过90%），达到行业领先水平。

The maximum motor speed of EHS electric mixing system is 16000rpm; Flat wire motor, the highest efficiency reached 97.5%, high efficiency zone accounted for up to 90.3% (high efficiency zone refers to the efficiency of more than 90%), reaching the industry-leading level.

一、研究意义与背景 Research background and significance

（六）如何实现全生命周期汽车零碳动力的思考 Thinking of how to realize the whole life cycle of the car zero carbon power

我国二氧化碳排放总量中，交通运输业占据**10%**，是全国碳排放**第三大户**，其中汽车占比贡献近**75%**。

The transport sector accounts for 10% of China's total carbon dioxide emissions and is the third largest carbon emitter in the country, with vehicles accounting for nearly 75%.

能源革命
- Well
- 油井

燃料革命
- Tank
- 邮箱

动力革命
- Wheels
- 车轮

- **如何进一步提升热效率？**
- **How to further improve thermal efficiency?**

效率水平是一个国家柴油机技术综合实力的标志和国际柴油机领域的前沿课题。柴油机热效率达到55%并实现产业化，将改写世界内燃机技术格局，对节能减排战略和碳达峰、碳中和战略目标的实现具有巨大推动作用。

The efficiency level is a symbol of the comprehensive strength of national diesel engine technology and an advanced topic in the field of international diesel engine. The thermal efficiency of diesel engine reaches 55% and realizes industrialization, which will rewrite the technical pattern of the world internal combustion engine, and greatly promote the realization of the strategy of energy conservation and emission reduction, carbon peak and carbon neutrality.

- **如何实现低碳/零碳燃料内燃机高效燃烧？**
- **How to realize efficient combustion of low-carbon/zero-carbon fuel internal combustion engine?**

提高内燃机热效率和采用低碳燃料和零碳燃料已经成为当前内燃机应对碳中和目标的必要手段。随着我国“碳达峰”与“碳中和”目标的提出，内燃机低碳化、零碳化势在必行。天然气、氢、氨都是未来极具竞争力的碳中和燃料。

Improving the thermal efficiency of internal combustion engine and using low carbon fuel and zero carbon fuel have become the necessary means to cope with the goal of carbon neutrality. Along with the proposal of our country "reaching peak carbon" and "carbon neutralization" goal, low carbon, zero carbon is imperative. Natural gas, hydrogen and ammonia are all highly competitive carbon-neutral fuels of the future.

二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（一）社会关注度显著提升-天然气 Significant increase in social awareness - Natural gas

《节能与新能源汽车技术路线图1.0》（2016年）

Energy-saving and New Energy Vehicle Technology Roadmap 1.0 (2016)

以发展天然气车辆为主要方向，因地制宜适度发展替代燃料汽车，推动我国汽车燃料的低碳化、多元化，降低对石油的依赖。**节能商用车方面，重中之重仍然是动力总成的能量转换效率，分别到了50%、52%和55%。天然气的商用车在未来会是替代燃料的主体之一。**

Taking the development of natural gas vehicles as the main direction, and moderately developing alternative fuel vehicles according to local conditions, promote our country's low-carbon and diversified automobile fuel, and reduce the dependence on petroleum. For fuel-efficient commercial vehicles, the top priority remains powertrain energy conversion efficiency at 50%, 52% and 55%, respectively. Natural gas commercial vehicles will be one of the main alternative fuels in the future.

《节能与新能源汽车技术路线图2.0》（2020年）

Energy-saving and New Energy Vehicle Technology Roadmap 2.0 (2020)

对商用汽车预计在2035年载货汽车油耗较2019年水平要下降15%—20%，客车油耗较2019年平均油耗要降低20%—25%。**替代燃料新车占传统乘用车的5%、8%、10%。掌握并应用稀薄燃烧及快速燃烧技术。**

For commercial vehicles, it is estimated that the fuel consumption of trucks and buses in 2035 will be reduced by 15%-20% compared with the 2019 level, and the average fuel consumption of buses will be reduced by 20%-25% compared with the 2019 level. New vehicles with alternative fuels account for 5, 8, 10 percent of traditional passenger vehicles. Master and apply thin combustion and fast combustion technology

二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（一）社会关注度显著提升-氢燃料 Significant increase in social awareness - Hydrogen

热门搜索：油价 数据要素 人工智能

中华人民共和国国家发展和改革委员会
National Development and Reform Commission

请输入关键字

首页 机构设置 新闻动态 政务公开 政务服务

首页 > 政务公开 > 解读 > 政策解读

国家发展改革委、国家能源局联合印发《氢能产业发展中长期规划（2021-2035年）》

发布时间：2022/03/23 来源：高技术司 [打印] 微博 微信

“氢能技术”重点专项 2022 年度
项目申报指南

为落实“十四五”期间国家科技创新有关部署安排，国家重点研发计划启动实施“氢能技术”重点专项。根据本重点专项实施方案的部署，现发布 2022 年度项目申报指南。

3.3 质子交换膜燃料电池与氢基内燃机混合发电系统技术（共性关键技术类）

研究内容：针对重载装备和分布式供电设备的高效灵活电源需求，开展质子交换膜燃料电池—氢基燃料内燃机混合发电系统关键技术研究。具体包括：单一现场氢基燃料（氨、醇、掺氢天然气等）的在线改质、纯化与实时调控技术及现场氢源总成研制，富氢和/或纯氢燃烧与循环调控技术及其内燃机研制，燃料电池系统—内燃机能量耦合机制及核心器件研制，现场氢源—燃料电池—氢内燃机全系统联合热力循环设计及建模仿真，发电系统各单元内部状态识别及动态工况调控策略，燃料电池—内燃机混合动力系统结构集成设计方法。

二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（一）社会关注度显著提升-氨燃料 Significant increase in social awareness - Ammonia

2022年度国家自然科学基金专项项目“氨燃料应用的若干基础问题研究”项目指南

日期 2022-11-03　来源：　作者：　【大 中 小】　【打印】　【关闭】

为推动面向国家“碳中和”的基础研究，国家自然科学基金委员会（以下简称自然科学基金委）交叉融合板块决定设立“氨燃料应用的若干基础问题研究”专项项目，针对氨燃料在能源动力系统中应用的核心科学问题，开展多学科交叉研究，为我国实现能源动力领域的“碳中和”提供科学依据和基础支撑。

一、科学目标

本项目旨在围绕氨燃料（包括以氨为主的混合燃料）动力系统，解决氨燃料点火难、燃烧慢、燃烧效率低、氮氧化物排放、能量循环利用效率等复杂问题，探索工程热物理、动力工程、流体力学、能源化学、环境化学、燃烧化学、材料学和人工智能等多领域的协同研究机制，为氨燃料能源动力系统低碳排放技术创新与应用奠定基础。

“重型车辆氨氢融合零碳动力系统基础研究”专项项目指南

日期 2022-03-15　来源：　作者：　【大 中 小】　【打印】　【关闭】

为推动面向国家碳中和的基础研究，国家自然科学基金委员会（以下简称自然科学基金委）交叉科学部拟设立“重型车辆氨氢融合零碳动力系统基础研究”专项项目，针对重型车用氨氢融合燃料及其高效近零排放的核心科学问题，开展多学科交叉研究，为我国实现重型运输装备的碳中和提供科学依据和基础支撑。

一、科学目标

本专项项目旨在围绕氨氢融合燃料和热、电复合动力系统，探索相关化学反应动力学、流体动力学、热力学和系统动力学的协同机制，建立氨氢融合燃料复合动力系统的设计理论与方法，解决车用氨燃料点火难、燃烧慢及动态控制复杂等问题，为重型运载车辆氨氢融合燃料复合动力系统零碳排放技术创新与应用奠定基础。

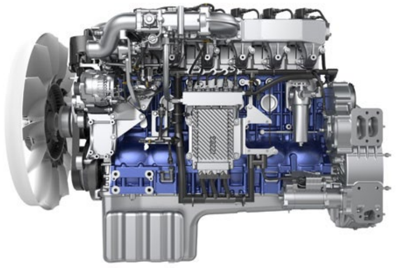
二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

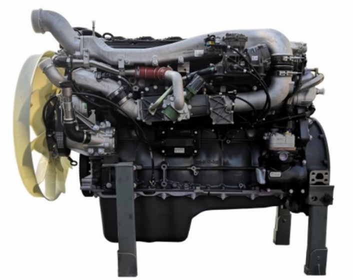
（二）研究现状及发展趋势-天然气发动机

Research status and development trend - Natural gas engine

主要技术指标		国际产品性能水平
动力性	最大功率（Ps）	460~570
	升功率(kW/L)	25~32
	升扭矩(N.m/L)	180~200
经济性	有效热效率(%)	38~41%
长寿命	B10寿命（万公里）	100
长保养	换油周期（万公里）	9
排放	排放水平	国六b


WP13NG 平台


CA6SM4 平台


MT13 平台


K13N 平台


12/15N 平台

二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（二）研究现状及发展趋势-天然气发动机

Research status and development trend - Natural gas engine

颠覆技术/超高热效率

Disruptive technology/Super-high thermal efficiency

压缩比、米勒循环、高能点火系统、EGR

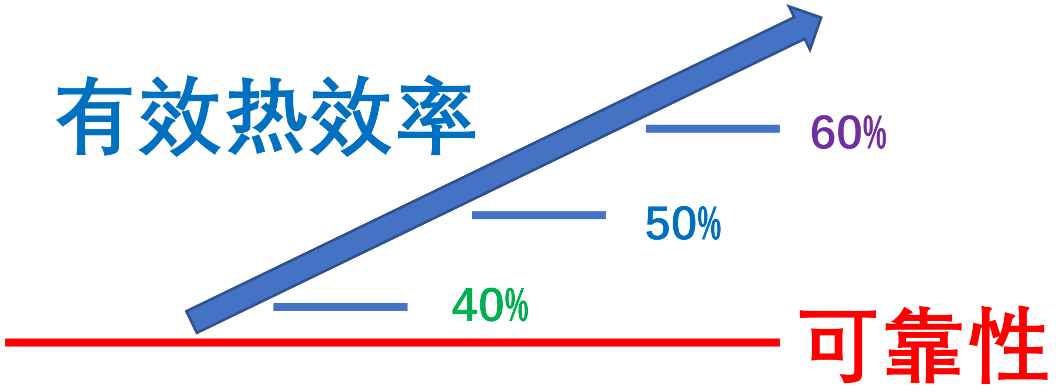
Compression ratio, Miller cycle, high-energy ignition system, EGR

射流点火、高湍动能燃烧室、高效稀薄燃烧

Jet ignition, high turbulent kinetic energy combustion chamber, efficient thin combustion

缸内直喷、超高压缩比

Direct injection in cylinder, ultra-high compression ratio



二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（二）研究现状及发展趋势-缸内直喷双燃料天然气发动机

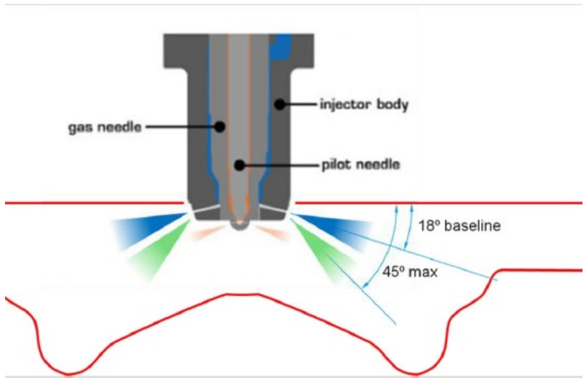
Research status and development trend - in-cylinder direct injection dual-fuel natural gas engine

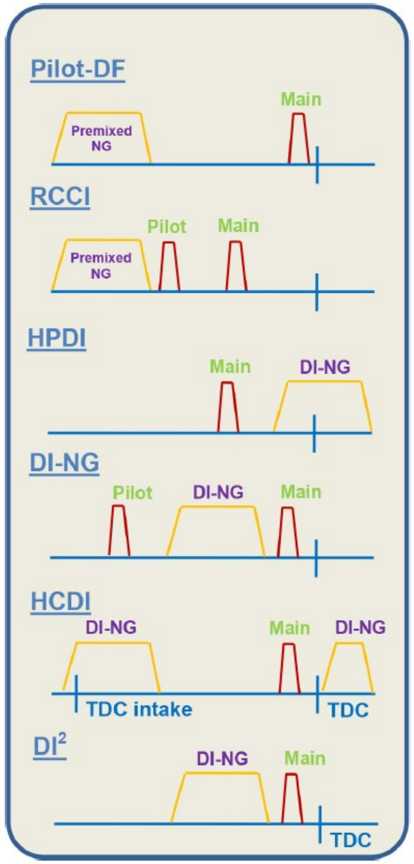
Efficiency and Emissions Characteristics of Partially Premixed Dual-Fuel Combustion by Co-Direct Injection of NG and Diesel Fuel (DI^2) - Part 2

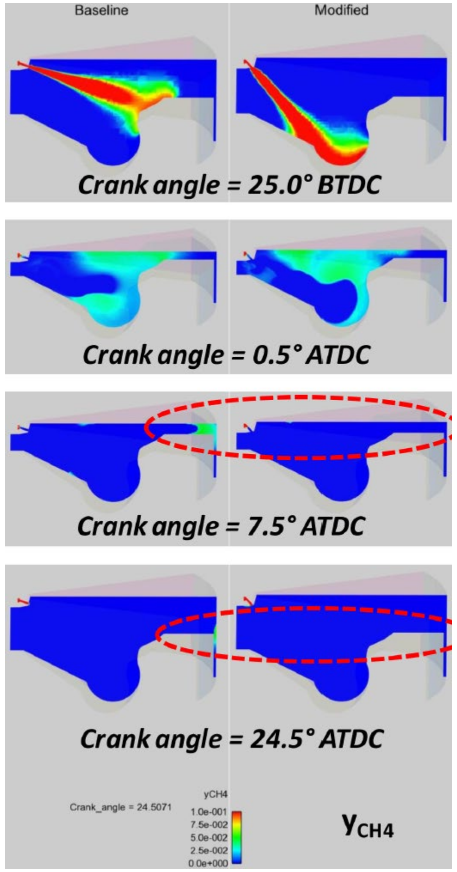
2017-01-0766
Published 03/28/2017

Gary D. Neely, Radu Florea, Jason Miwa, and Zainal Abidin
Southwest Research Institute

CITATION: Neely, G., Florea, R., Miwa, J., and Abidin, Z., "Efficiency and Emissions Characteristics of Partially Premixed Dual-Fuel Combustion by Co-Direct Injection of NG and Diesel Fuel (DI2) - Part 2," SAE Technical Paper 2017-01-0766, 2017, doi:10.4271/2017-01-0766.







二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（二）研究现状及发展趋势-缸内直喷双燃料天然气发动机

Research status and development trend - in-cylinder direct injection dual-fuel natural gas engine

Fuel 308 (2022) 121920

Contents lists available at ScienceDirect

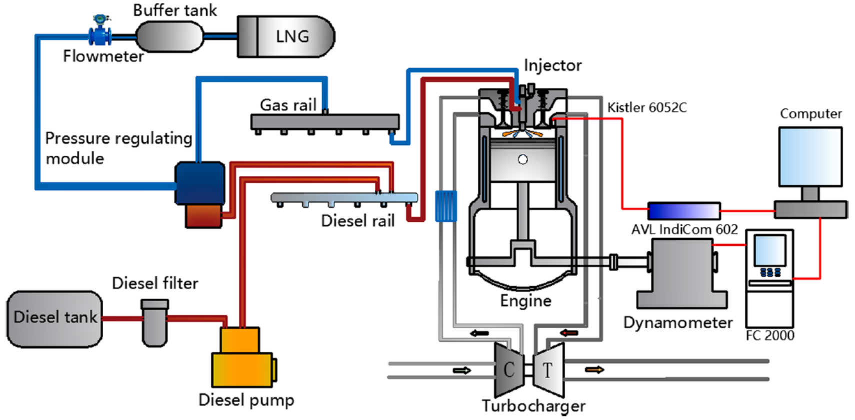
Fuel

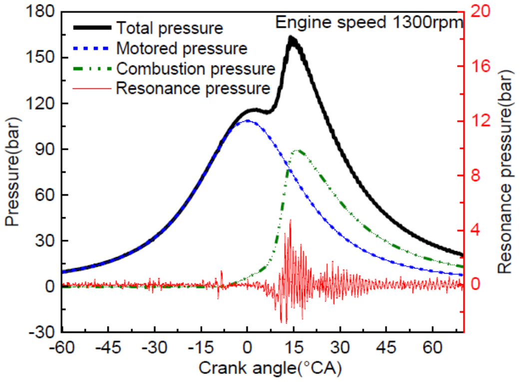
journal homepage: www.elsevier.com/locate/fuel

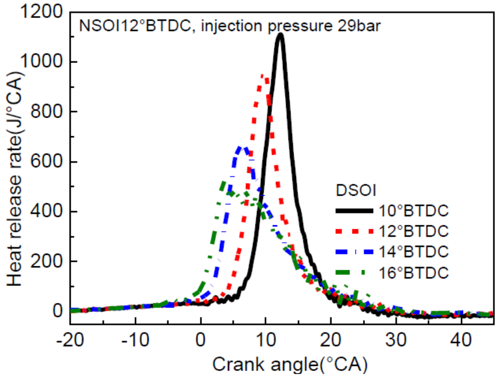
Effects of injection strategy on the knocking behavior of a pilot ignited direct injection natural gas engine

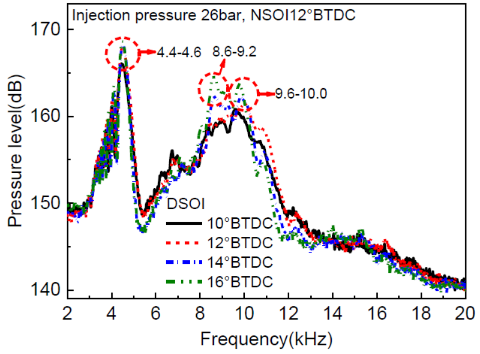
Qiang Zhang [a], Guangshu Song [a], Xiaoyan Wang [b], Menghan Li [c,*]

[a] School of Energy and Power Engineering, Shandong University, Jinan 250061, China
[b] Weichai Power Co., Ltd., 197A Fushou East Street, High-Tech Development Zone, Weifang, Shandong 261001, China
[c] Hebei Key Laboratory of Thermal Science and Energy Clean Utilization, School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin 300401, China









二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（二）研究现状及发展趋势-缸内直喷双燃料天然气发动机

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Energy 270 (2023) 126813

ELSEVIER

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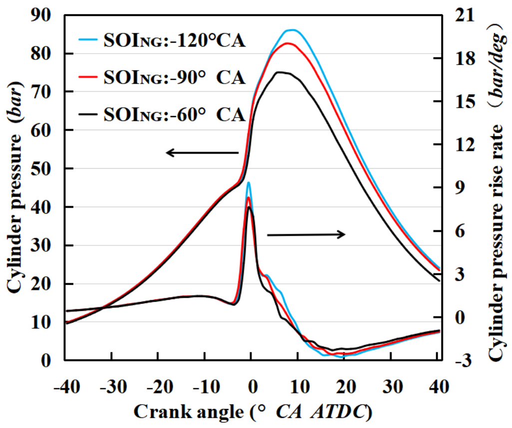
Energy

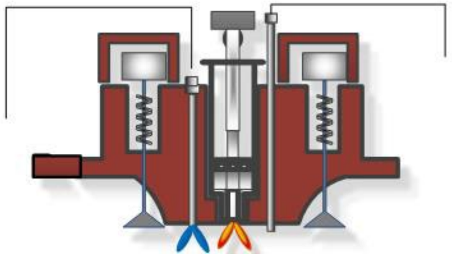
journal homepage: www.elsevier.com/locate/energy

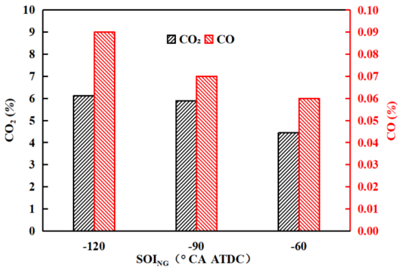
Impact of natural gas injection timing on the combustion and emissions performance of a dual-direct-injection diesel/natural gas engine

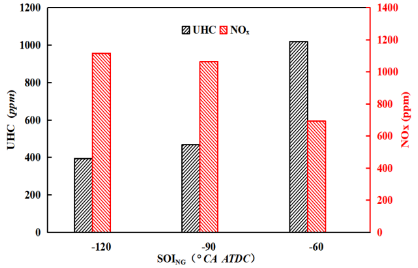
Kailin Yang, Zhongshu Wang *, Kechao Zhang, Dan Wang, Fangxi Xie, Yun Xu, Kaiqiang Yang

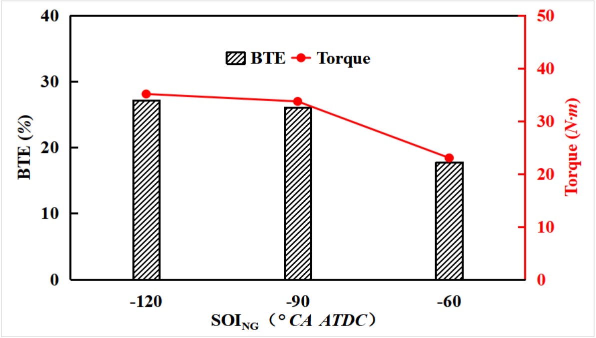
State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130025, China









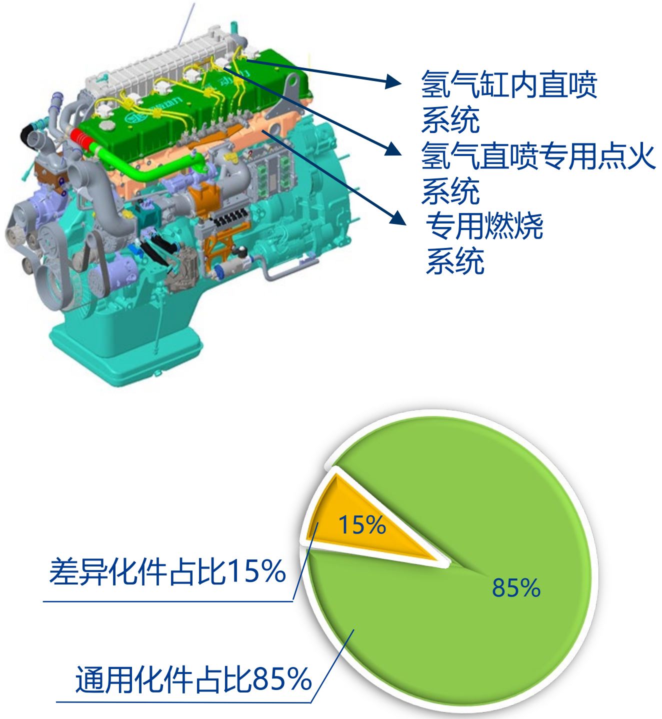


二、低碳/零碳燃料发动机发展趋势及研究现状

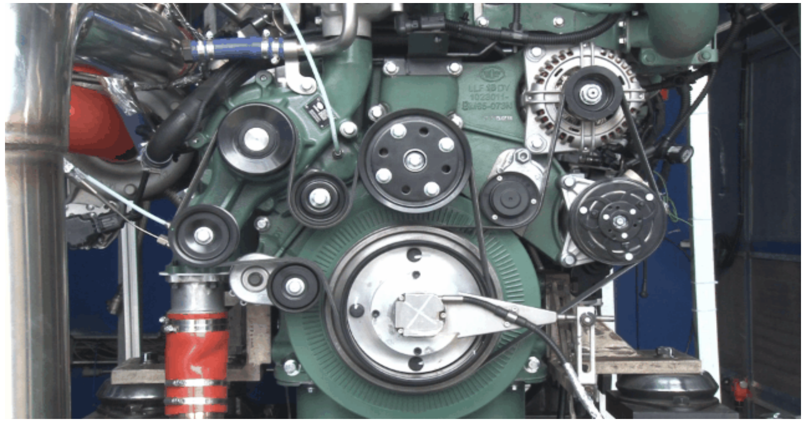
Development trend and research status of low-carbon/zero-carbon fuel engine

（二）研究现状及发展趋势-氢燃料发动机

Research status and development trend - Hydrogen-fueled engine



天然气发动机与氢气发动机结构差异



二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（二）研究现状及发展趋势-氨燃料发动机

Research status and development trend - Ammonia-fueled engine

绿色环保：氨是零碳燃料，可利用可再生能源制备

Green: Ammonia is a zero-carbon fuel that can be prepared from renewable energy sources

多领域应用：已在船机、燃气轮机、火箭发动机中应用

Multi-field application: It has been applied in ship engine, gas turbine and rocket engine

储运方便：常温9bar或常压-33℃可液化，利于储运

Storage and transportation: It can be liquefied at room temperature of 9bar or atmospheric pressure of -33℃, which is conducive to storage and transportation

能量密度高：比氢气和天然气能量密度高，续航里程长

High energy density: Higher energy density than hydrogen and natural gas, long driving range

特性\燃料	氨	氢	柴油	天然气
（当前技术条件）密度 /g•cm^{-3}	0.77	0.071	0.84	0.187
能量密度/MJ•L^{-3}	11.5	4.8	35.2	9.7
当量混合气热值/MJ•kg^{-1}	2.64	3.36	2.79	2.87

氨燃料存在点火难与燃烧慢的问题： **Ammonia fuel has problems of difficult ignition and slow combustion:**

相比于传统碳氢燃料，氨的反应活性低、自燃温度高，其最小点火能为汽油的60倍以上，层流火焰速度约为汽油的1/5，这大大提高了氨内燃机的开发难度。

Compared with traditional hydrocarbon fuels, ammonia has low reactivity and high spontaneous combustion temperature, its minimum ignition energy is more than 60 times that of gasoline, and laminar flame speed is about 1/5 of gasoline, which greatly improves the difficulty of the development of ammonia internal combustion engine.

现有解决方案： **Existing solutions:**

柴油引燃、氨氢融合（在线裂解制氢）、火花点燃……

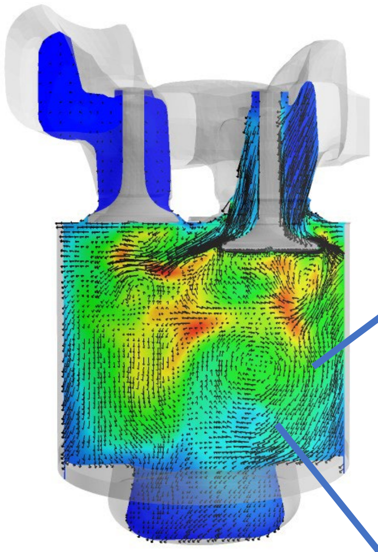
Diesel ignition, ammonium-hydrogen fusion (online cracking hydrogen production), spark ignition...

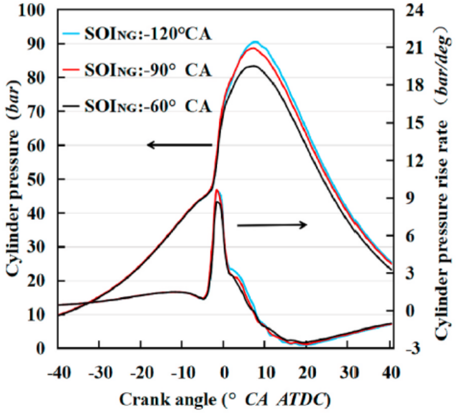
二、低碳/零碳燃料发动机发展趋势及研究现状

Development trend and research status of low-carbon/zero-carbon fuel engine

（三）双燃料发动机-燃烧过程评价方法的局限

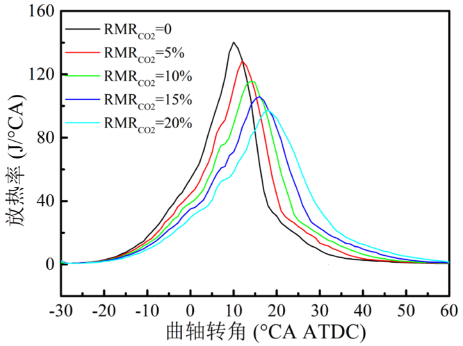
Dual-fuel engine-Limitations of combustion process evaluation methods





缸压、缸压升高率

Cylinder pressure, cylinder pressure rise rate



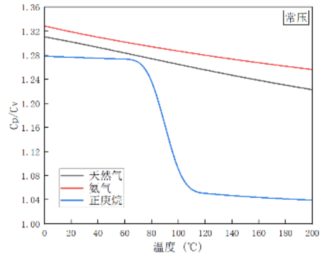
放热率

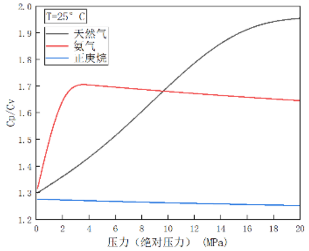
heat release rate

放热率计算公式通常根据热力学第一定律计算

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta}$$

$$\gamma = \frac{C_p}{C_V}$$





不同燃料的比热比是不同的，且随缸内温度及压力变化较大，导致了放热率计算结果存在一定的误差。

The specific heat ratio of different fuels is different, and varies greatly with the temperature and pressure in the cylinder, leading to a certain error in the calculation result of heat release rate.

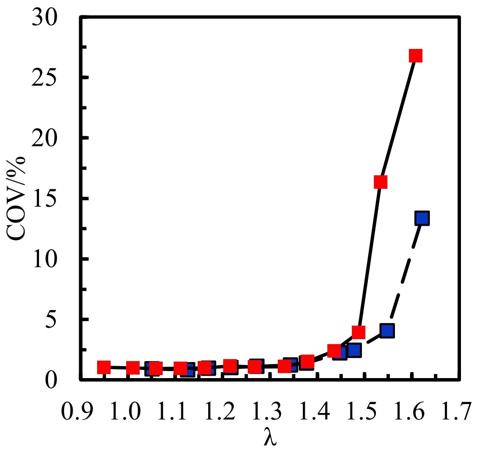
为了进一步明晰双燃料发动机燃烧机理，提高发动机工作性能，亟需提出的适于双燃料发动机的评价方法及体系。

In order to further clarify the combustion mechanism of dual-fuel engine and improve the performance of the engine, it is urgent to put forward the evaluation method and system suitable for dual-fuel engine.

三、一种适于双燃料发动机燃烧过程的评价方法

An evaluation method suitable for dual-fuel engine combustion process

（一）方法的提出-受“循环变动”启发 Proposed method - Inspired by "cyclic variation"



燃烧循环变动：

Combustion cycle variation:

燃烧循环变动对于点燃式发动机来说是一个老问题。如果比较连续多个循环，可以发现缸内最大压力值及其所对应的曲轴转角差别很大。点燃式发动机的燃烧循环变动对燃料经济性和排放均有很大的负面影响。

Combustion cycle variation is an old problem for ignition engines. If multiple cycles are compared, it can be found that the maximum pressure in the cylinder and the corresponding crankshaft angle are very different. The combustion cycle variation of ignition engine has a great negative effect on fuel economy and emission.

引起发动机燃烧循环变动的因素是多方面的，Heyhood（1988）把引起燃烧循环变动的主要影响因素总结为点火时刻缸内混合气运动状态的变动；每循环进气量和燃料供给量的变动；每循环残余废气质量的变动，尤其是火花塞附近区域的变动。

There are many factors that cause the combustion cycle variation of the engine. Heyhood (1988) summarized the main factors that cause the combustion cycle variation as the movement state of the mixture in the cylinder at the time of ignition. Changes in gas intake and fuel supply per cycle; Variation in the mass of residual exhaust gas per cycle, especially in the area around the spark plug.

另外，所有延缓燃烧过程的因素，以及一个新的物理及变化过程的引入，都将促使循环变动加大，如稀燃、EGR以及低负荷工况等。

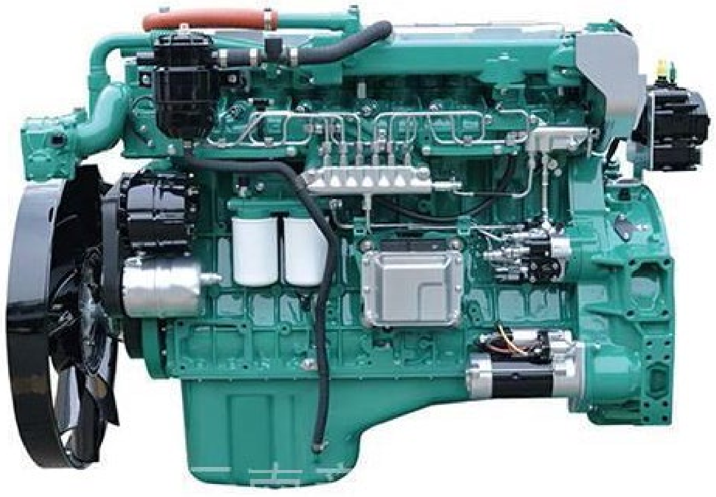
In addition, all the factors that slow down the combustion process, as well as the introduction of a new physical and variable process, will increase the cycle variability, such as thin burn, EGR, and low-load conditions.

三、一种适于双燃料发动机燃烧过程的评价方法

An evaluation method suitable for dual-fuel engine combustion process

（二）评价方法-基于缸压变动

Evaluation method - Based on cylinder pressure variation



CA6DL 双燃料发动机

技术参数	指标
发动机型式	直列、六缸、增压中冷、高压共轨、四气门
总排量/L	8.6
压缩比	17.2
缸径×冲程	112×145
额定功率/kW	260（2100/r·min^{-1}）
最高转速/r·min^{-1}	2415
最大扭矩/N·m	1500（1400/r·min^{-1}）
燃烧室类型	缩口ω形

三、一种适于双燃料发动机燃烧过程的评价方法

An evaluation method suitable for dual-fuel engine combustion process

（二）评价方法-基于缸压变动

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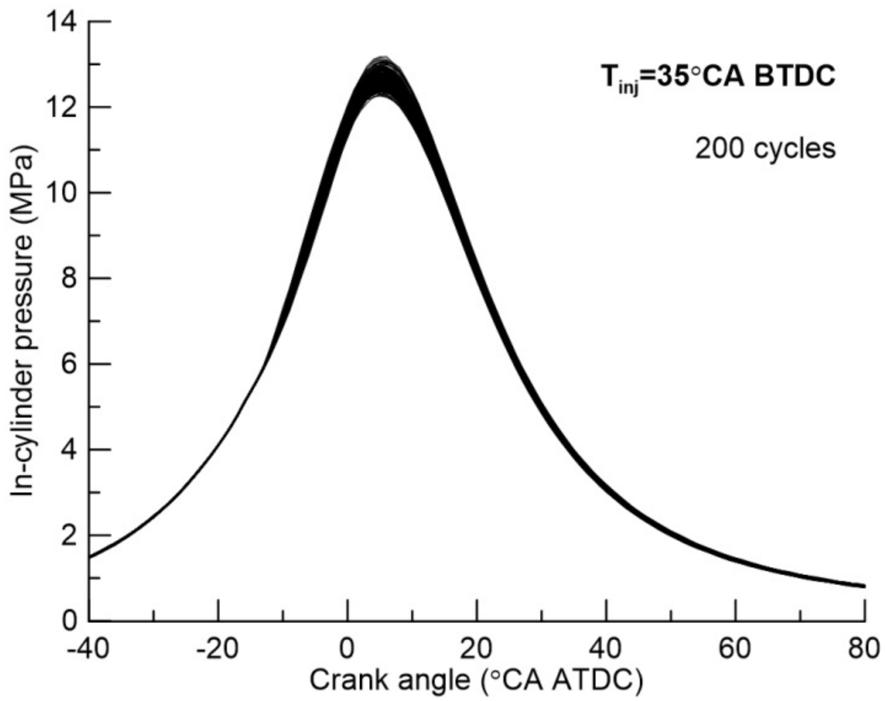


In-cylinder pressure traces of 200 cycles with T_{inj} 35°CA BTDC.

这里定义平均压力为$\mu_p(\theta)$，缸压变动标准差$\sigma_p(\theta)$，缸压变动系数$COV_p(\theta)$，公式如下所示：

the average pressure is defined as $\mu_p(\theta)$
standard deviation of cylinder pressure variation $\sigma_p(\theta)$
coefficient of cylinder pressure variation $COV_p(\theta)$
the formula is shown below:

$$\mu_\mathrm{p}(\theta) = \frac{1}{NC}\sum_{i=1}^{NC} p_i(\theta)$$

$$\sigma_\mathrm{p}(\theta) = \left[\frac{1}{NC}\sum_{i=1}^{NC}\left(p_i(\theta) - \mu_\mathrm{p}(\theta)\right)^2\right]^{1/2}$$

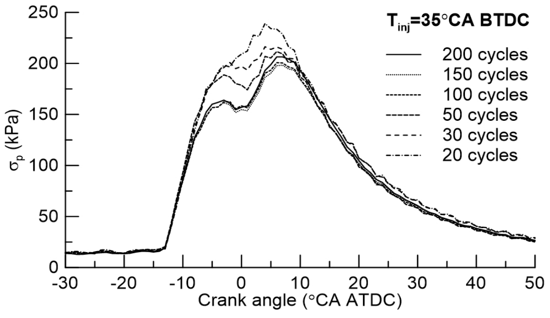
$$\mathrm{COV}_\mathrm{p}(\theta) = \frac{\sigma_\mathrm{p}(\theta)}{\mu_\mathrm{p}(\theta)} \cdot 100\%$$

三、一种适于双燃料发动机燃烧过程的评价方法

An evaluation method suitable for dual-fuel engine combustion process

（二）评价方法-基于缸压变动

Evaluation method - Based on cylinder pressure variation



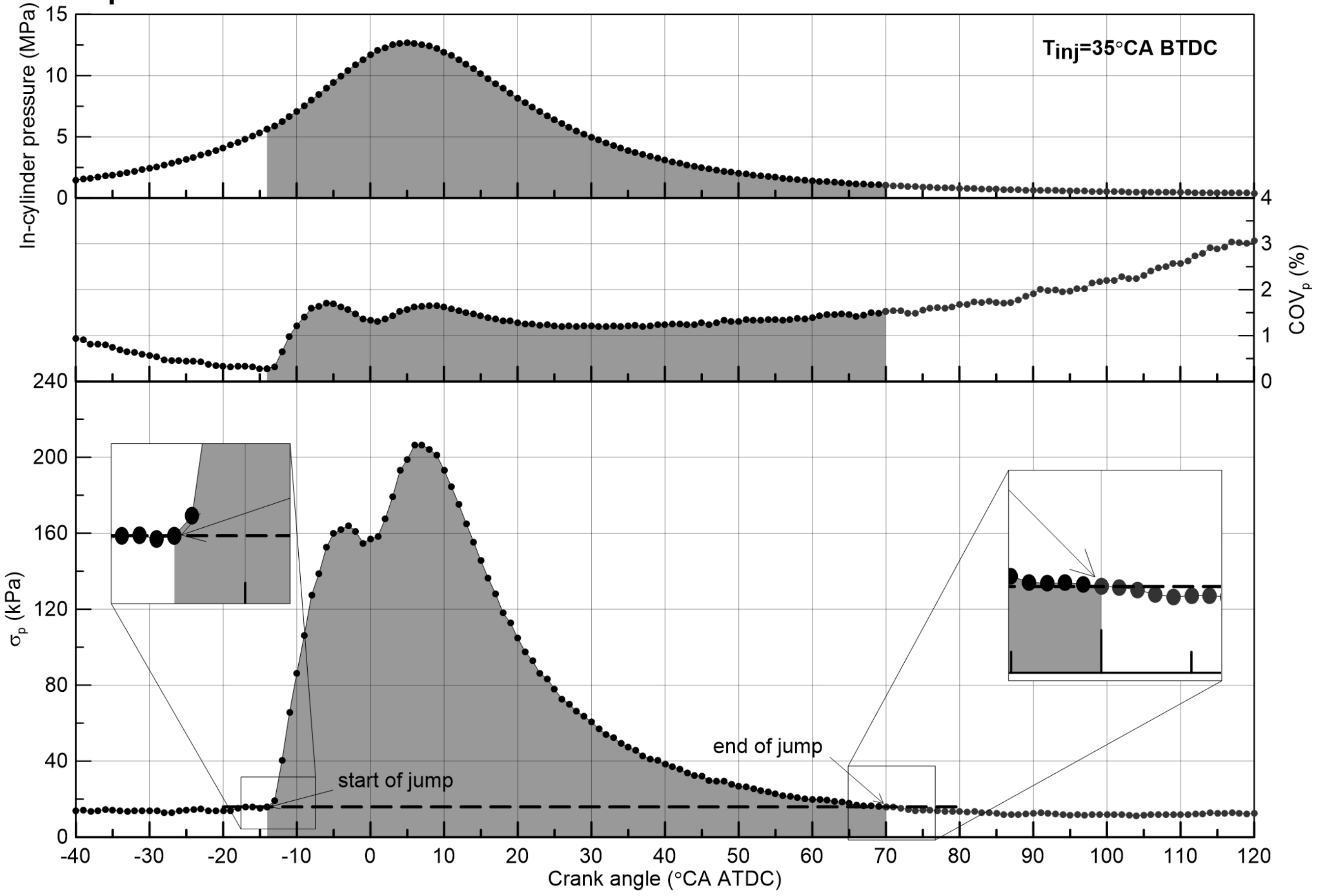
Standard deviation traces with different sample numbers.

通过对采集样本数对结果影响的分析与评价，选取200循环作为样本数。

Through the analysis and evaluation of the influence of the sample number on the results, 200 cycles were selected as the sample number.

右图为平均压力为$\mu_p(\theta)$，缸压变动标准差$\sigma_p(\theta)$，缸压变动系数$COV_p(\theta)$，在1975r/min, 25%load工况下的变化规律，可见具有一定的规律性。

In the figure on the right, the average pressure is $\mu_p(\theta)$, the standard deviation of cylinder pressure variation $\sigma_p(\theta)$, and the coefficient of cylinder pressure variation $COV_p(\theta)$ under the working condition of 1975r/min and 25%load, showing a certain regularity.



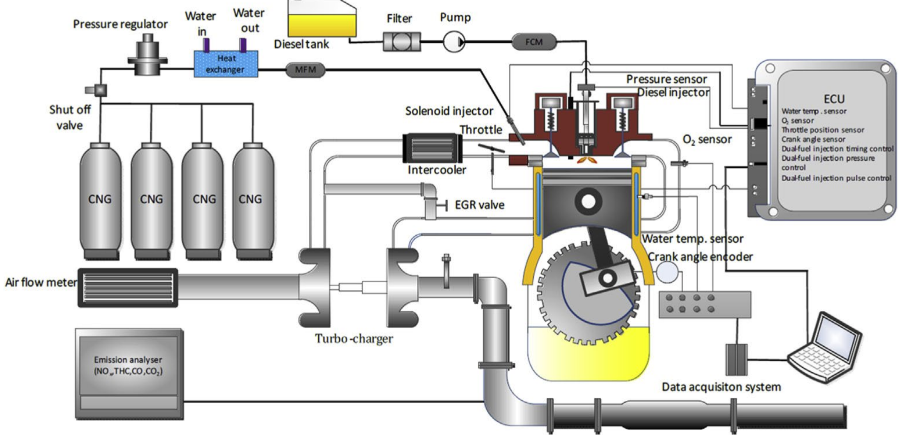
In-cylinder pressure, COV and standard deviation profiles with T_{inj} 35°CA BTDC.

三、一种适于双燃料发动机燃烧过程的评价方法

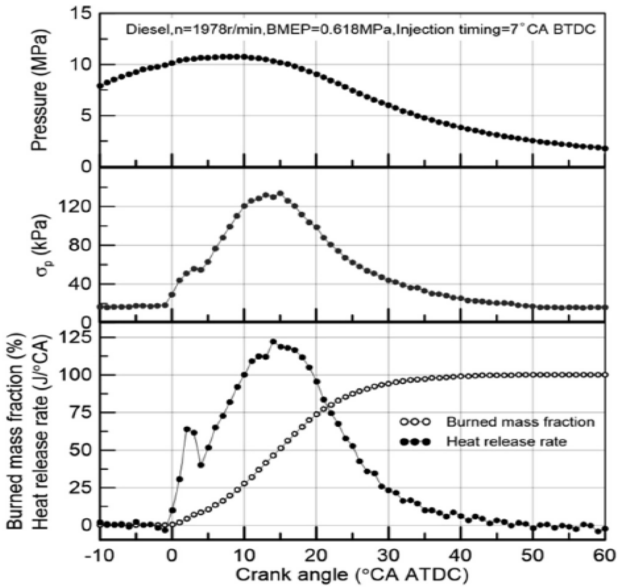
An evaluation method suitable for dual-fuel engine combustion process

（三）新的评价方法-对比验证

New evaluation methods - Comparative Validation



Schematic diagram of the engine test rig



Combustion evaluation with different methods using single diesel fuel.

为了确定所提出的方法的有效性，对单一燃用柴油工况进行了比对分析，如上所示，可见具有较好的映射关系。

In order to determine the effectiveness of the proposed method, a comparative analysis of single diesel fuel conditions was carried out, as shown above, showing a good mapping relationship.

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A novel combustion evaluation method based on in-cylinder pressure traces for diesel/natural gas dual fuel engines

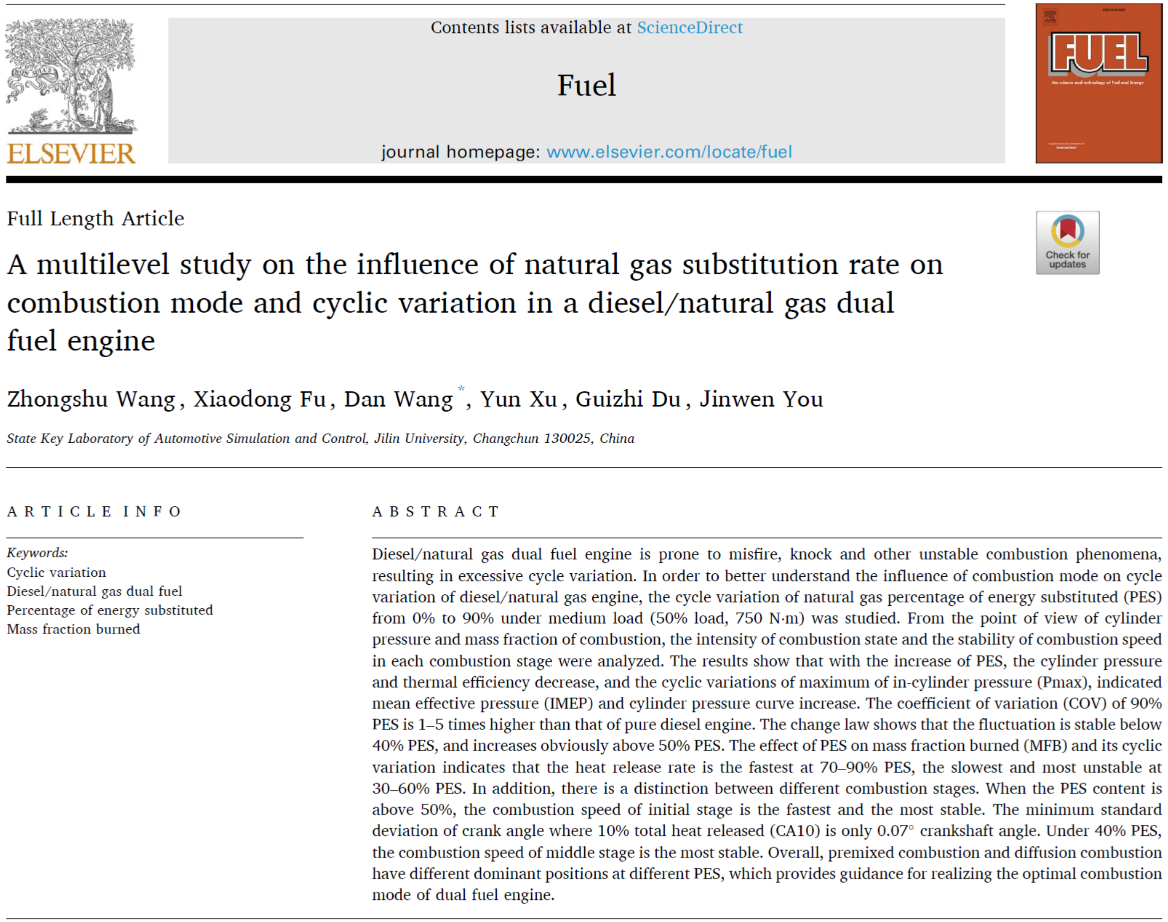
Zhongshu Wang [a], Wenjing Chen [a], Dan Wang [a, *], Manzhi Tan [a], Zhongchang Liu [a], Huili Dou [b]

四、基于该方法的双燃料发动机性能评价

Performance evaluation of dual-fuel engine based on this method

（一）燃料替代率对燃烧过程的影响分析

Analysis of the effect of fuel substitution rate on combustion process



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FUEL

Full Length Article

A multilevel study on the influence of natural gas substitution rate on combustion mode and cyclic variation in a diesel/natural gas dual fuel engine

Zhongshu Wang, Xiaodong Fu, Dan Wang *, Yun Xu, Guizhi Du, Jinwen You

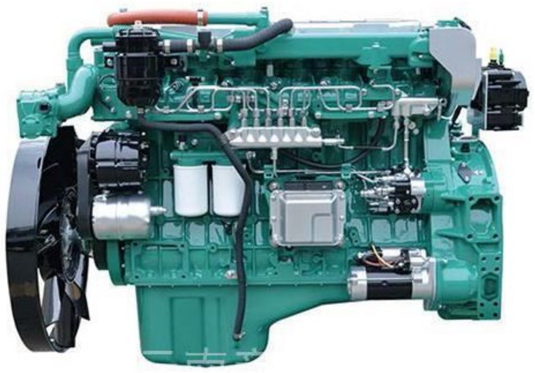
State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130025, China

ARTICLE INFO

Keywords:
Cyclic variation
Diesel/natural gas dual fuel
Percentage of energy substituted
Mass fraction burned

ABSTRACT

Diesel/natural gas dual fuel engine is prone to misfire, knock and other unstable combustion phenomena, resulting in excessive cycle variation. In order to better understand the influence of combustion mode on cycle variation of diesel/natural gas engine, the cycle variation of natural gas percentage of energy substituted (PES) from 0% to 90% under medium load (50% load, 750 N·m) was studied. From the point of view of cylinder pressure and mass fraction of combustion, the intensity of combustion state and the stability of combustion speed in each combustion stage were analyzed. The results show that with the increase of PES, the cylinder pressure and thermal efficiency decrease, and the cyclic variations of maximum of in-cylinder pressure (Pmax), indicated mean effective pressure (IMEP) and cylinder pressure curve increase. The coefficient of variation (COV) of 90% PES is 1–5 times higher than that of pure diesel engine. The change law shows that the fluctuation is stable below 40% PES, and increases obviously above 50% PES. The effect of PES on mass fraction burned (MFB) and its cyclic variation indicates that the heat release rate is the fastest at 70–90% PES, the slowest and most unstable at 30–60% PES. In addition, there is a distinction between different combustion stages. When the PES content is above 50%, the combustion speed of initial stage is the fastest and the most stable. The minimum standard deviation of crank angle where 10% total heat released (CA10) is only 0.07° crankshaft angle. Under 40% PES, the combustion speed of middle stage is the most stable. Overall, premixed combustion and diffusion combustion have different dominant positions at different PES, which provides guidance for realizing the optimal combustion mode of dual fuel engine.



技术参数	指标
发动机型式	直列、六缸、增压中冷、高压共轨、四气门
总排量/L	8.6
压缩比	17.2
缸径×冲程	112×145
额定功率/kW	260（2100/r·min^{-1}）
最高转速/r·min^{-1}	2415
最大扭矩/N·m	1500（1400/r·min^{-1}）
燃烧室类型	缩口ω形

四、基于该方法的双燃料发动机性能评价

Performance evaluation of dual-fuel engine based on this method

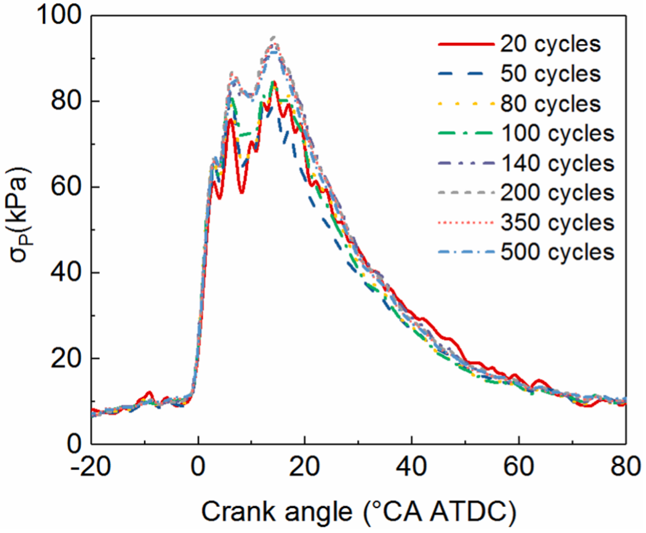
（一）燃料替代率对燃烧过程的影响分析-工况选取

Influence analysis of fuel substitution rate on combustion process - selection of operating conditions

工况选取A（1335r/min）和B （16555r/min）转速，50%负荷，

天然气能量替代率0~90%。循环样本数选择为140个循环。

The working conditions select A (1335r/min) and B (16555r/min) speed, 50% load, natural gas energy replacement rate 0~90%. The number of cycle samples was selected as 140 cycles.



Standard deviation of in-cylinder pressure in eight groups of samples.

$$PES = \frac{\dot{m}_{NG} \times LH_{NG}}{\dot{m}_{NG} \times LH_{NG} + \dot{m}_{diesel} \times LH_{diesel}} \times 100\%$$

$$\lambda = \frac{\dot{m}_{air}}{\dot{m}_{NG} \times AFR_{NG}^{th} + \dot{m}_{diesel} \times AFR_{diesel}^{th}}$$

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

Engine operating parameters.

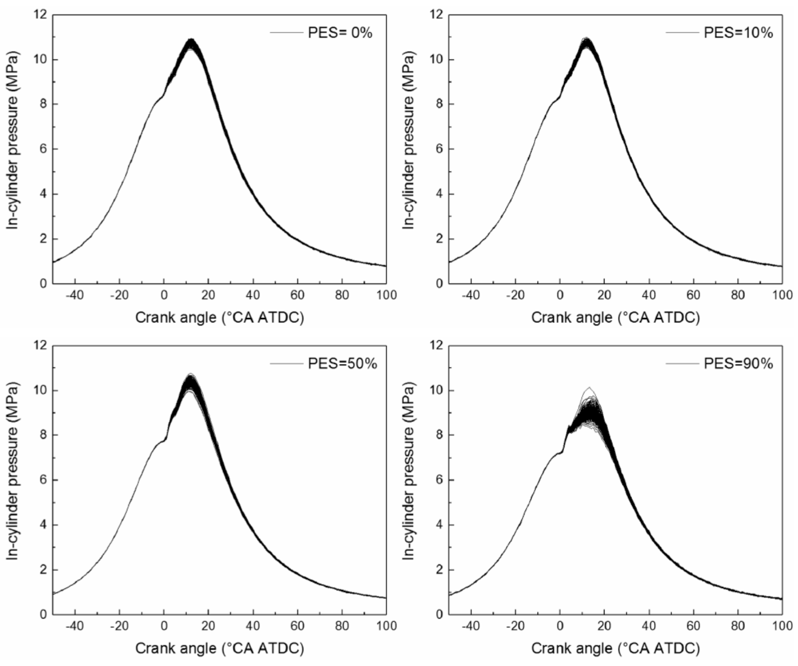
PES %	Speed r/min	Torque N·m	Diesel kg/h	NG kg/h	Air kg/h	λ	η %
0	1335	688	19.97	0	614.5	2.35	39.86
10	1335	676	18.06	1.80	613.6	2.32	38.85
20	1334	664	16.02	3.50	606.7	2.29	38.30
30	1334	651	14.02	5.23	601.3	2.27	37.57
40	1334	639	11.98	6.99	592.1	2.23	36.91
50	1334	631	10.02	8.66	584.4	2.21	36.52
60	1335	624	8.00	10.43	578.6	2.16	36.12
70	1335	620	6.05	12.22	570.0	2.12	35.69
80	1335	613	4.05	13.86	564.6	2.09	35.49
90	1335	583	2.02	15.75	557.3	2.06	33.52
0	1655	654	24.70	0	892.9	2.93	37.97
10	1655	642	22.23	2.29	882.8	2.91	37.03
20	1655	620	19.86	4.29	860.9	2.74	35.87
30	1655	605	17.44	6.42	847.6	2.63	34.96
40	1655	588	14.89	8.65	831.4	2.61	33.96
50	1655	577	12.41	10.83	822.5	2.41	33.29
60	1655	562	9.95	13.03	807.7	2.34	32.34
70	1655	535	7.42	15.15	793.1	2.21	30.90
80	1655	489	4.96	17.21	773.3	2.14	28.35
90	1655	410	2.46	19.32	725.9	1.92	23.84

四、基于该方法的双燃料发动机性能评价

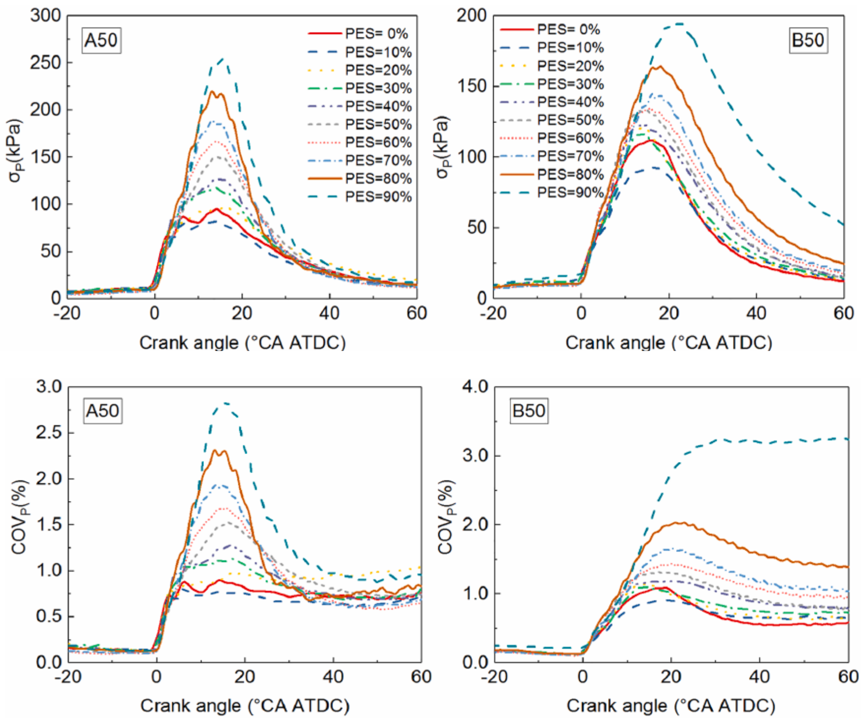
Performance evaluation of dual-fuel engine based on this method

（一）燃料替代率对燃烧过程的影响分析-缸压、变动标准差、变动系数、BMEP

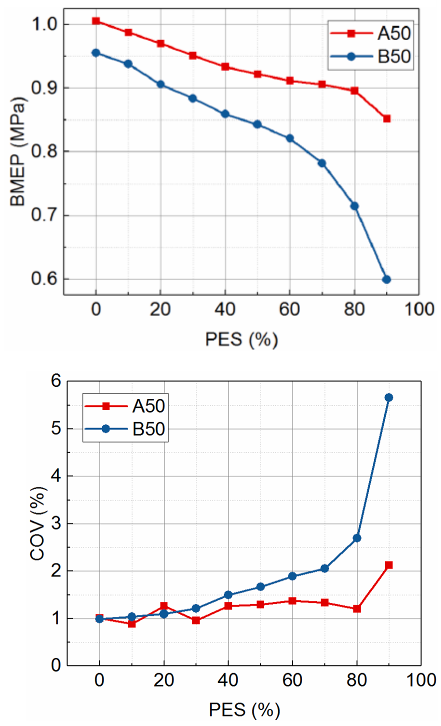
Analysis of the effect of fuel replacement rate on combustion process - cylinder pressure, variation standard deviation, variation coefficient, BMEP



In-cylinder pressure curve of different PES (0%, 10%, 50%, 90%) under 140 cycles.



COV of in-cylinder pressure with crank angle for different PES at A50 and B50.



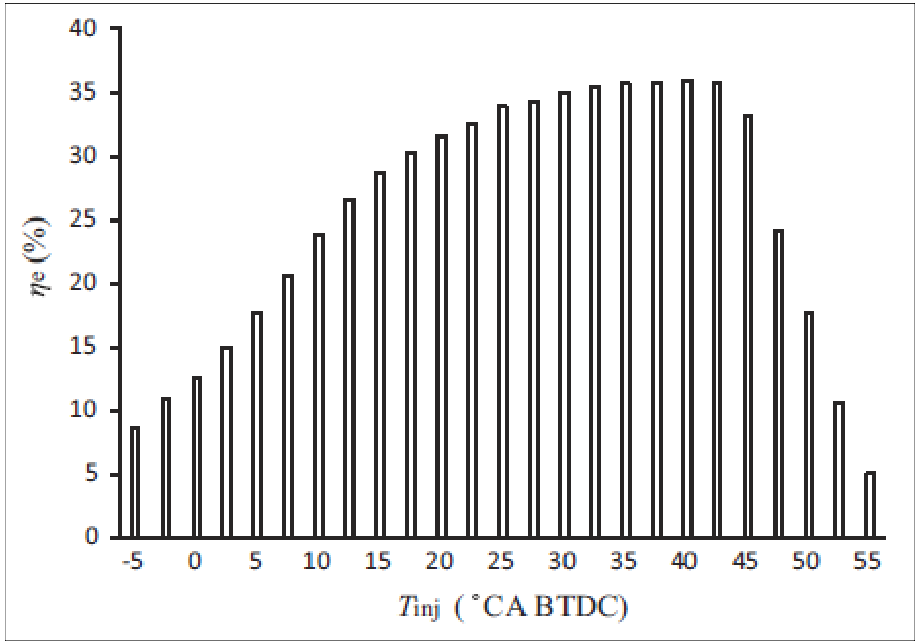
BMEP and its COV with different PES at A50 and B50.

四、基于该方法的双燃料发动机性能评价

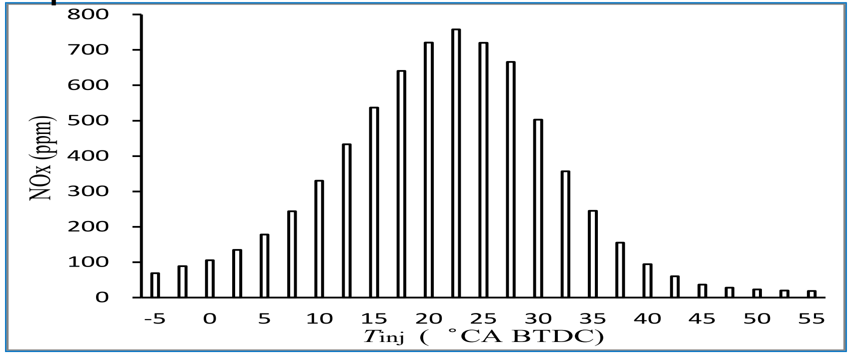
Performance evaluation of dual-fuel engine based on this method

（二）引燃模式对燃烧过程的影响分析-性能

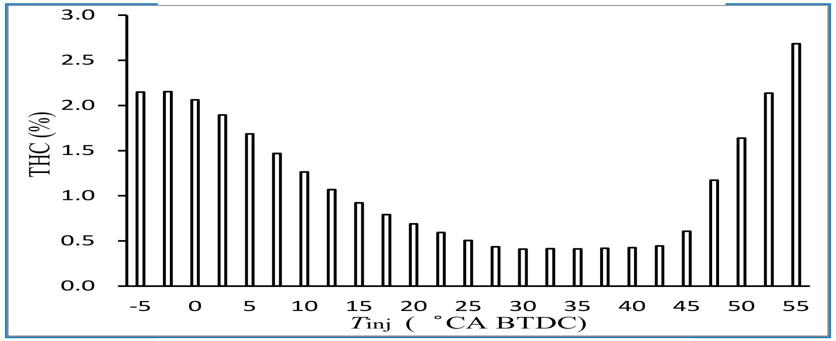
Analysis of the effect of ignition mode on combustion process - Performance



Effect of T_{inj} on engine thermal efficiency at 1335 r/min.



Effect of T_{inj} on NOx emissions at 1335 r/min.



Effect of T_{inj} on THC emissions at 1335 r/min.

试验研究发现对于双燃料发动机而言，柴油喷射时刻对于柴油的燃烧过程及随后的天然气燃烧过程，以及发动机排放性能有着至关重要的影响。

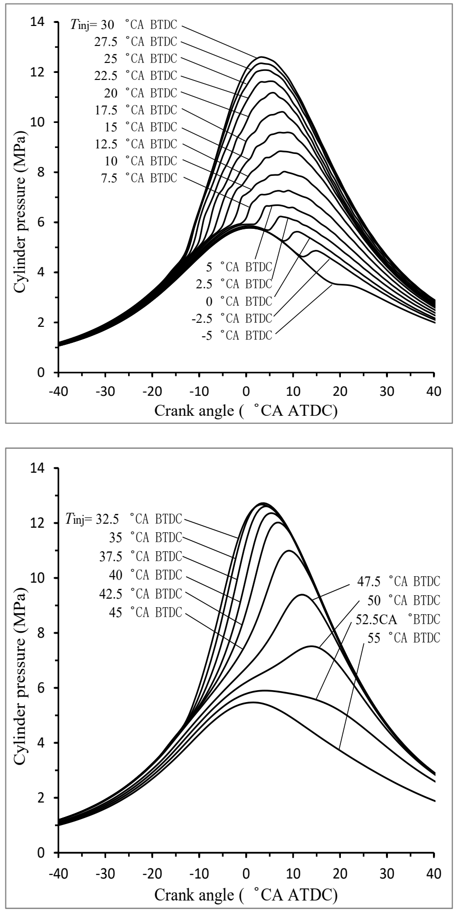
It is found that for dual-fuel engines, diesel injection timing has a crucial impact on diesel combustion process and subsequent natural gas combustion process, as well as engine emission performance.

四、基于该方法的双燃料发动机性能评价

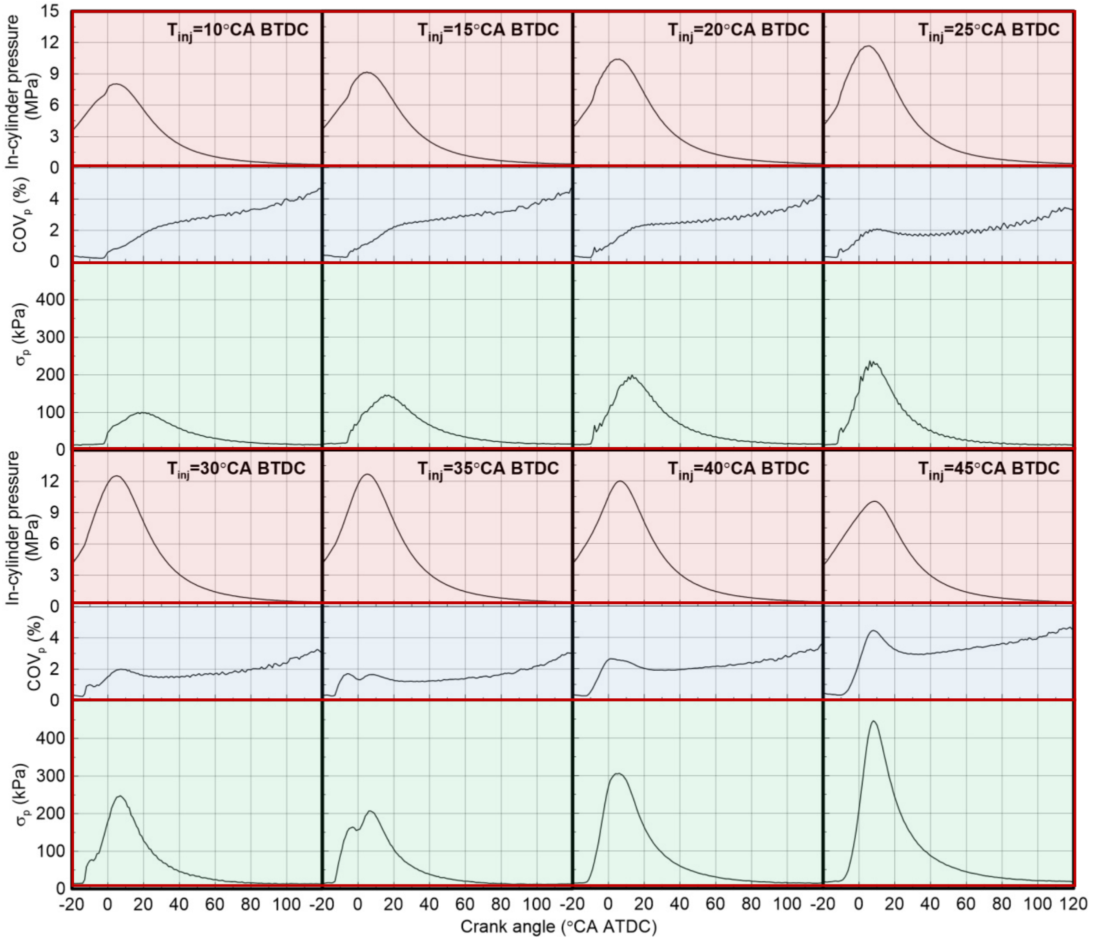
Performance evaluation of dual-fuel engine based on this method

（二）引燃模式对燃烧过程的影响分析-缸压及缸压变动

Analysis of the effect of ignition mode on combustion process - Cylinder pressure and cylinder pressure variation



Pressure profiles with T_{inj} at 1335 r/min.



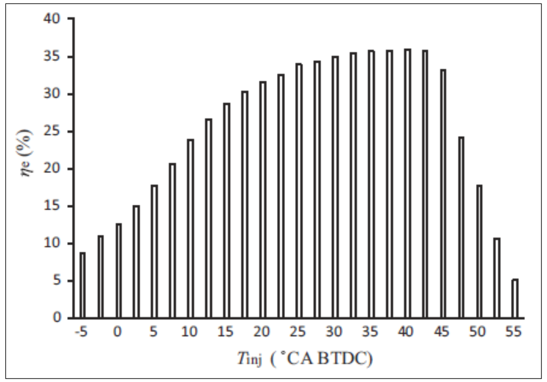
In-cylinder pressure, COV and standard deviation profiles for various diesel injection timings.

四、基于该方法的双燃料发动机性能评价

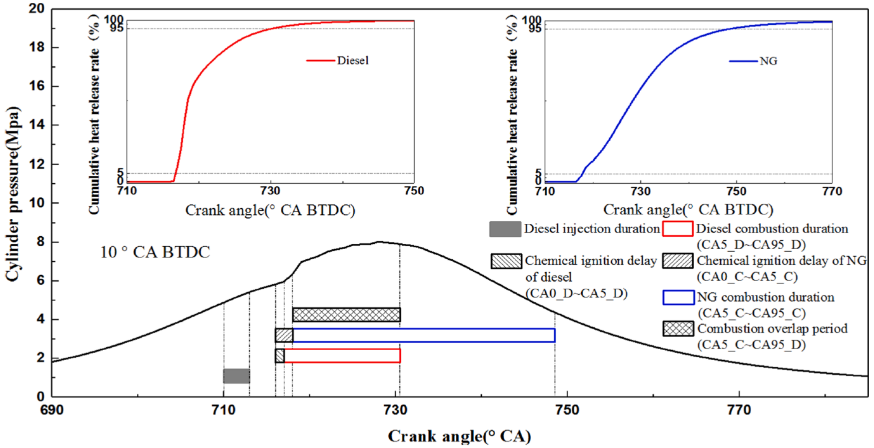
Performance evaluation of dual-fuel engine based on this method

（二）引燃模式对燃烧过程的影响分析-燃烧过程解耦分析

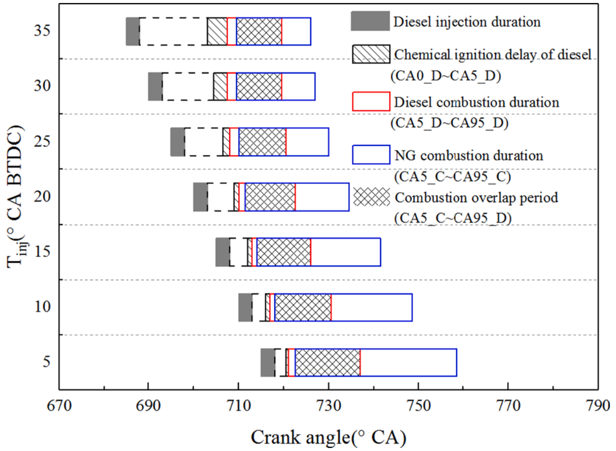
Influence analysis of ignition mode on combustion process - Decoupling analysis of combustion process



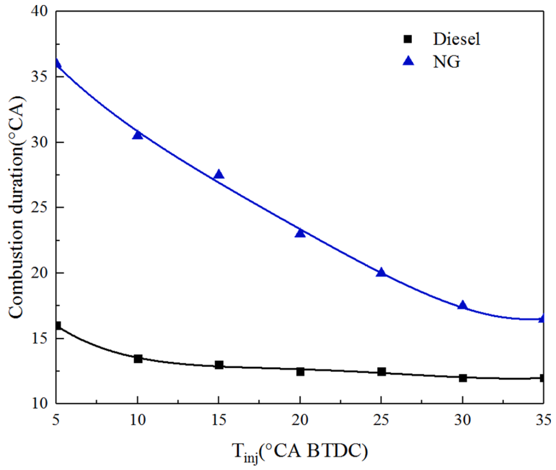
Effect of T_{inj} on engine thermal efficiency at 1335 r/min.



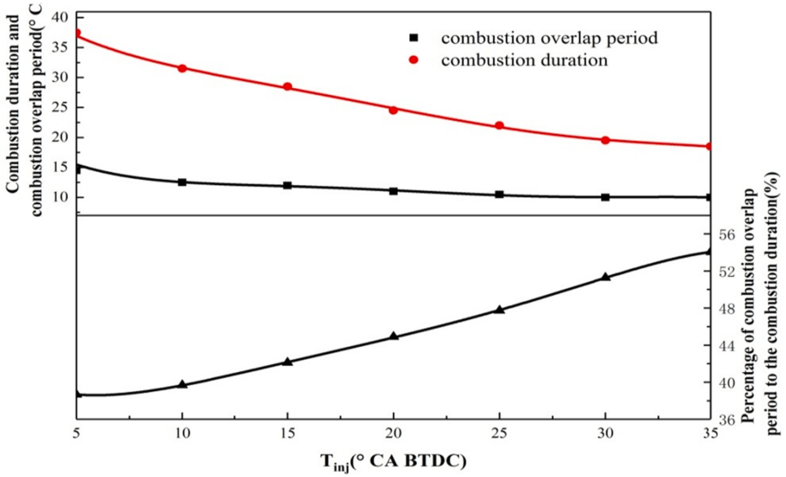
The combustion phase and cumulative heat release rate at 10° CA BTDC.



Combustion phases of the diesel and the NG



Combustion duration of diesel and NG.

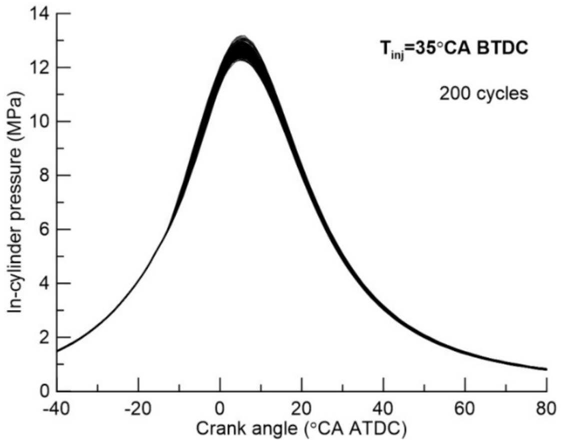


Analyses of combustion results.

五、结束语 Conclusion

- 提出了一种基于缸压变动的双燃料发动机燃烧过程评价方法，为未来超高热效率发动机性能的提升提供了新的思考思路。

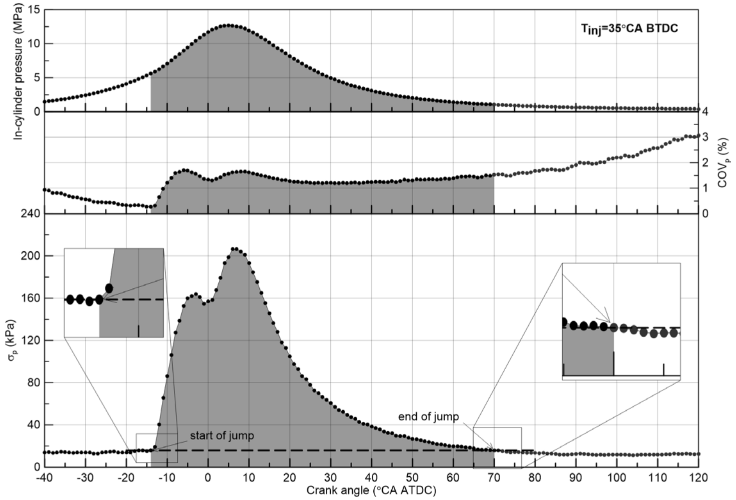
A combustion process evaluation method of dual-fuel engine based on cylinder pressure variation is proposed, which provides support for the future performance improvement of ultra-high thermal efficiency engines.



$$\mu_p(\theta) = \frac{1}{NC}\sum_{i=1}^{NC} p_i(\theta)$$

$$\sigma_p(\theta) = \left[\frac{1}{NC}\sum_{i=1}^{NC}\left(p_i(\theta) - \mu_p(\theta)\right)^2\right]^{1/2}$$

$$\mathrm{COV}_p(\theta) = \frac{\sigma_p(\theta)}{\mu_p(\theta)} \cdot 100\%$$



五、结束语 Conclusion

本团队发表相关学术文章列表：

List of relevant academic articles published by our team:

1. Impact of natural gas injection timing on the combustion and emissions performance of a dual-direct-injection diesel/natural gas engine , **DOI: 10.1016/j.energy.2023.126813**
2. Impact of ignition energy on the combustion performance of an SI heavy-duty stoichiometric operation natural gas engine, **DOI: 10.1016/j.fuel.2021.122857**
3. Impacts of the horizontal swirl and axial tumble on the turbulent kinetic energy and combustion process of a natural gas engine, **DOI: 10.1080/15567036.2021.1965263**
4. A multilevel study on the influence of natural gas substitution rate on combustion mode and cyclic variation in a diesel/natural gas dual fuel engine, **DOI: 10.1016/j.fuel.2021.120499**
5. Combustion phase of a diesel/natural gas dual fuel engine under various pilot diesel injection timings, **DOI: 10.1016/j.fuel.2020.119869**
6. Experimental analysis of inert gases in EGR on engine power and combustion characteristics in a stoichiometric dual fuel heavy-duty natural gas engine ignited with diesel, **DOI: 10.1016/j.applthermaleng.2020.115860**
7. Study on the effect of water addition on combustion characteristics of a HCCI engine fueled with natural gas, **DOI: 10.1016/j.fuel.2020.117547**
8. Theoretical Analyses of Heat Balance in a Diesel/Natural Gas Dual-Fuel Engine at Low and Medium Loads Based on Experimental Values, **DOI: 10.1115/1.4046760**
9. The exhausted gas recirculation improved brake thermal efficiency and combustion characteristics under different intake throttling conditions of a diesel/natural gas dual fuel engine at low loads, **DOI: 10.1016/j.fuel.2020.117035**
10. Effect of EGR and Fuel Injection Strategies on the Heavy-Duty Diesel Engine Emission Performance under Transient Operation, **DOI: 10.3390/en13030566**
11. Impact of natural gas injection strategies on combustion and emissions of a dual fuel natural gas engine ignited with diesel at low loads, **DOI: 10.1016/j.fuel.2019.116414**
12. Combustion process decoupling of a diesel/natural gas dual-fuel engine at low loads, **DOI: 10.1016/j.fuel.2018.05.152**
13. Impact of pilot diesel ignition mode on combustion and emissions characteristics of a diesel/natural gas dual fuel heavy-duty engine, **DOI: 10.1016/j.fuel.2015.11.077**

五、结束语 Conclusion

发展车辆零碳动力
助力我国交通运输领域实现双碳目标

Develop zero-carbon power for vehicles
Help China's transportation sector to achieve the double-carbon goal

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

感 谢 您 的 聆 听!

Thank you for listening!