Research and Development of HCNG Internal Combustion Engines

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清能华通
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发展HCNG、CNG汽车的背景和意义

Background and Significance of Developing HCNG and CNG Vehicles

- 环保节能及实现我国汽车工业跨越式发展的挑战

  Environment protection, energy saving and the challenges of development of China auto industry

  - 石油依赖性和国家能源安全

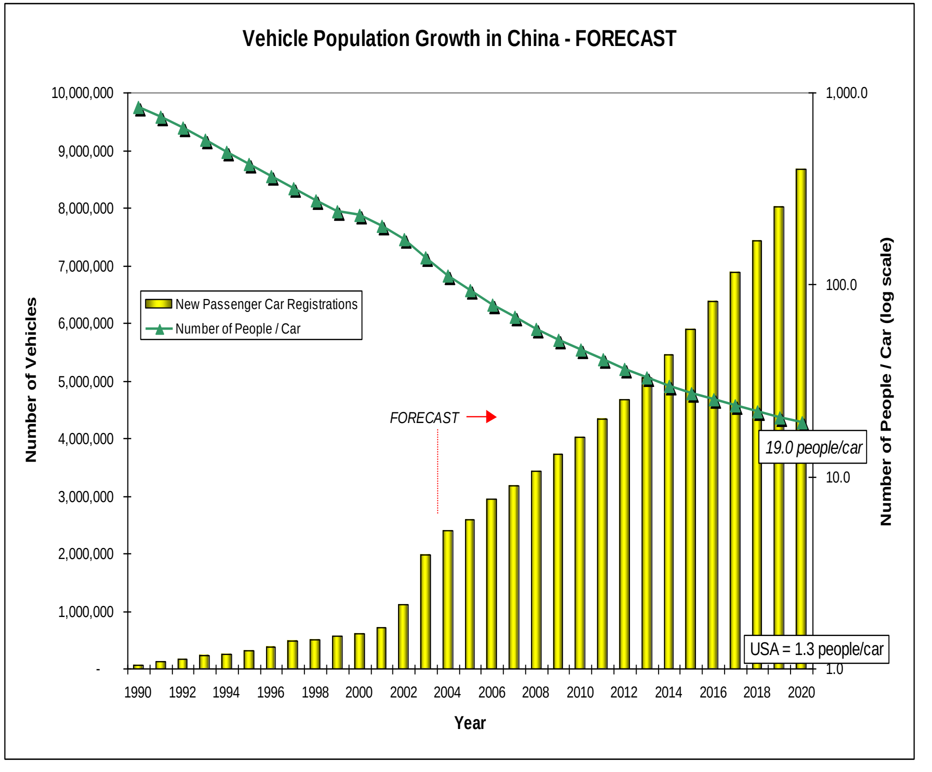
    Oil dependence and China's energy security

  - 汽车保有量增加，污染加剧

    Vehicle population growing and environment pollution aggravating

  - 未来氢能发展提供的机遇

    Opportunity from hydrogen energy development in the future



发展HCNG、CNG汽车的背景和意义

Background and Significance of Developing HCNG and CNG Vehicles

- 在天然气发动机燃料中加入适量的氢气（即氢气/天然气混合气，简称"**HCNG**"），可以提高混合气燃烧速度、扩大稀燃极限，从而提高发动机的热效率、可降低排放，这是目前国内外正在研究的热点问题。
Taking hydrogen enriched compressed natural gas (HCNG) as a fuel in CNG engine can increase the burning speed, widen the lean burn limit. For its high efficiency and better emission, HCNG engine is being studied worldwide.

- 近年来，国外开展了**HCNG**发动机的基础研究及应用研究，其中美国、加拿大、欧盟日本等国的研究最为活跃。在美国能源部（**DOE**）等支持下，美国**Colorado**州立大学、**HCI**公司（**Hydrogen Components Inc.**）、加拿大**Westport**等单位较早就开始了氢气/天然气发动机的研究，取得了许多研究开发及示范应用成果。
In recent years, some countries carried out the basic research on HCNG engine actively, especially in the USA, Canada，EU and Japan.
With the supports of Department of Energy (DOE) etc., Colorado University HCI company (Hydrogen Components Inc.) ,Westport Inc. etc. started the research on HCNG engine early, and got lots of achievements of research and demonstration.

发展HCNG、CNG汽车背景和意义
Background and Significance of Developing HCNG and CNG Vehicles

Cummins – Westport's HCNG Engine

Engine	Cummins-Westport B Gas plus 6 cylinders，inline, Turbocharged and intercooled
Bore，Stroke	102mm, 120mm
Compression Ratio	10.5：1
Displacement	5.9 L
H2/HCNG by volume	20%
Power	230 BHP (172 Kw) @ 2800 RPM
Torque	677 Nm @ 1600 RPM

HCNG buses demonstration in Sunline Transit, California, USA

从天然气汽车到氢能汽车的发展路径

The Development Path from CNG Vehicles to Hydrogen Vehicles

- H_2 作为内燃机汽车燃料是过渡
- HCNG（ H_2+CNG ）

存在问题：

- 排放标准偏低
- 甲烷排放
- 燃料经济性比柴油机低20%—40%
- 续行里程不够长

天然气汽车

- 满足欧Ⅱ排放
- 火花点燃式内燃机
- 100%天然气
- 天然气加气站

解决氢能汽车一般性问题

HCNG混合燃料汽车

- 满足欧Ⅲ以上排放标准,动力性提高
- 机械式动力传动系统
- 点燃式内燃机
- HCNG混合燃料
- 天然气加气站+制氢设备

解决氢能电动汽车特殊性问题

气—电混合电动汽车

- 满足欧Ⅳ以上排放标准,
- 燃料消耗下降15%以上,动力增加
- 串联式机电混合动力系统
- 火花点燃式内燃发电机组
- HCNG混合燃料
- 天然气加气站+制氢设备

解决燃料电池电动汽车实用化问题

氢燃料电池汽车

- 零排放,
- 燃料消耗下降25%以上,动力增加
- 价格与纯电动汽车相当
- 串联混合动力传动
- 燃料电池发动机
- 100%氢气燃料(压缩氢气)
- 天然气加气站+重整制氢设备

HCNG、CNG发动机试验台
HCNG and CNG engine’s Test Bench

发动机与电涡流测功相连，可测量和控制转速与负荷。

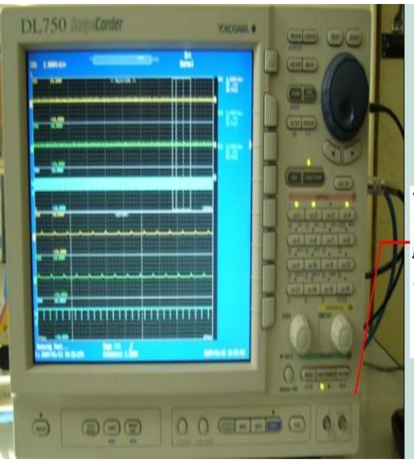
The engine was coupled to an eddy-current dynamometer for engine speed & load measurement and control.

CNG and HCNG Engine’s Experimental Systems

- Three performance 、emission experiment benches
- Reliability test base in Nanchong Dongfeng
- CVS total flow test equipment and transient test-bed
- catalyst test bench

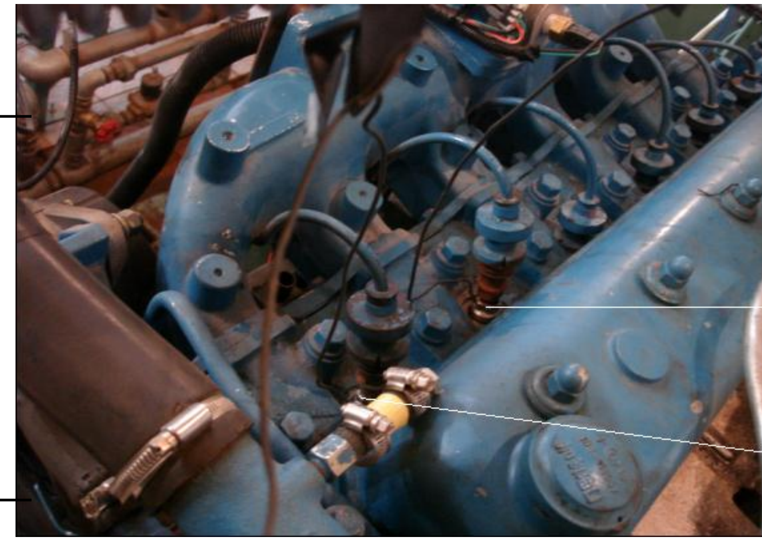
发动机缸内压力的测量系统

Engine’s In-cylinder Pressure Measurement System



YOKOGAWA 采集仪

KISTLER角标仪

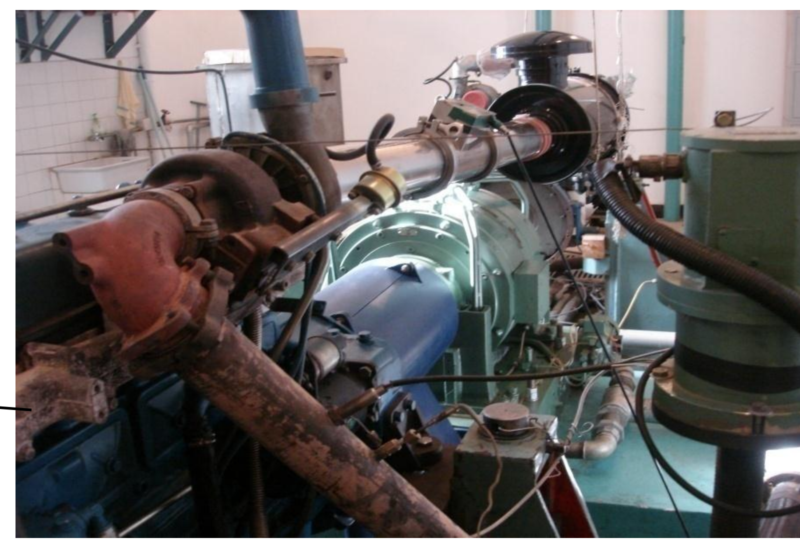


2缸传感器的安装位置

1缸传感器的安装位置

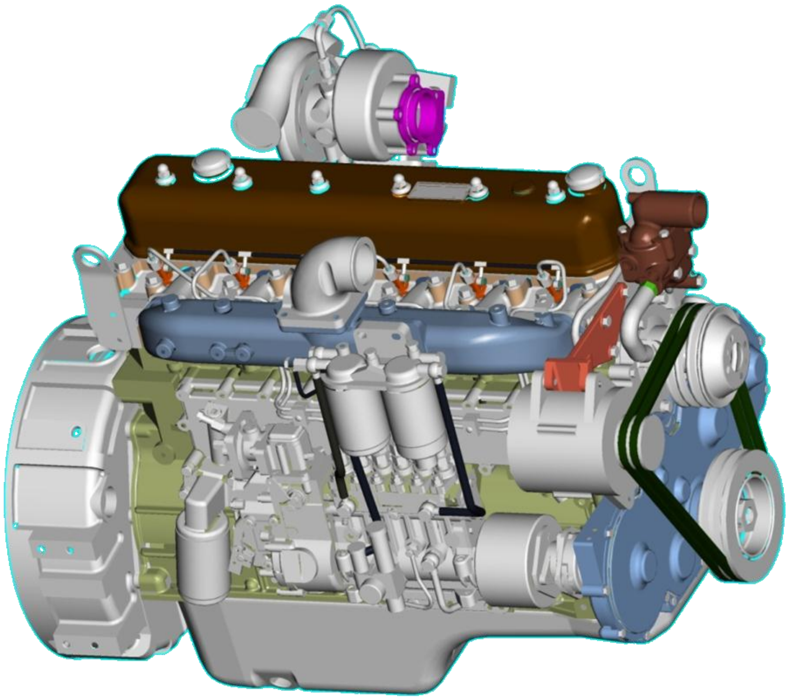
KISTLER电荷放大器

HORIBA空然比仪



Engine

The test engine was an in-line 6-cylinder, throttle body injection one designed for city bus application. It was modified from a diesel engine by replacing fuel injector with spark plug and reshaping the piston head to reduce compression ratio.



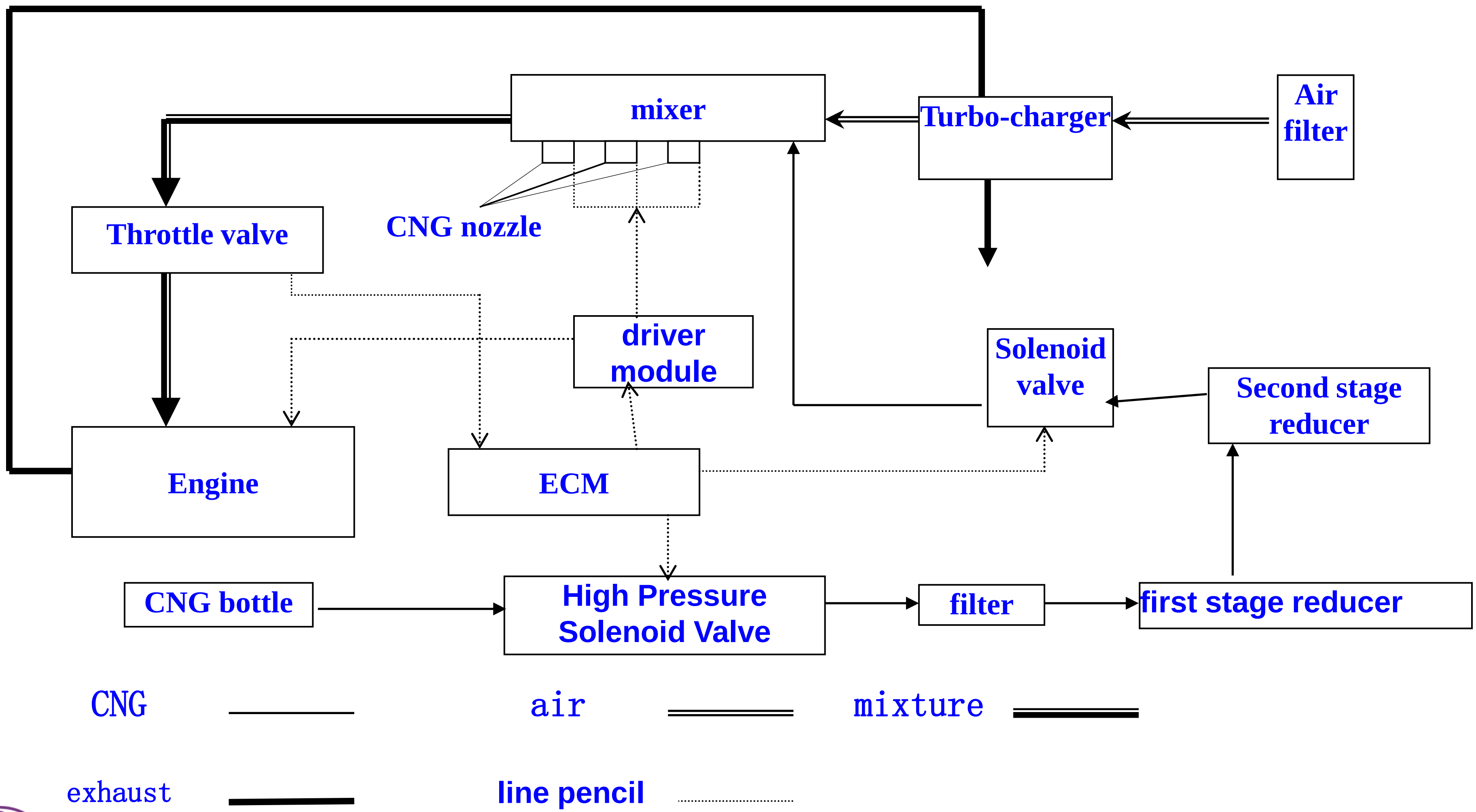
Technical Approach of the Engine

- **电子控制CNG进气管喷射**
  Electronic control CNG injection in the engine's manifold
- **空燃比开环控制→闭环控制**
  Open → Close－ loop control of Air-Fuel ratio
- **电控高能点火**
  High-energy ignition with electronic control
- **稀薄燃烧**
  Lean burn
- **水冷式增压器**
  water-cooled supercharger
- **氧化型催化器**
  Oxidation catalyst

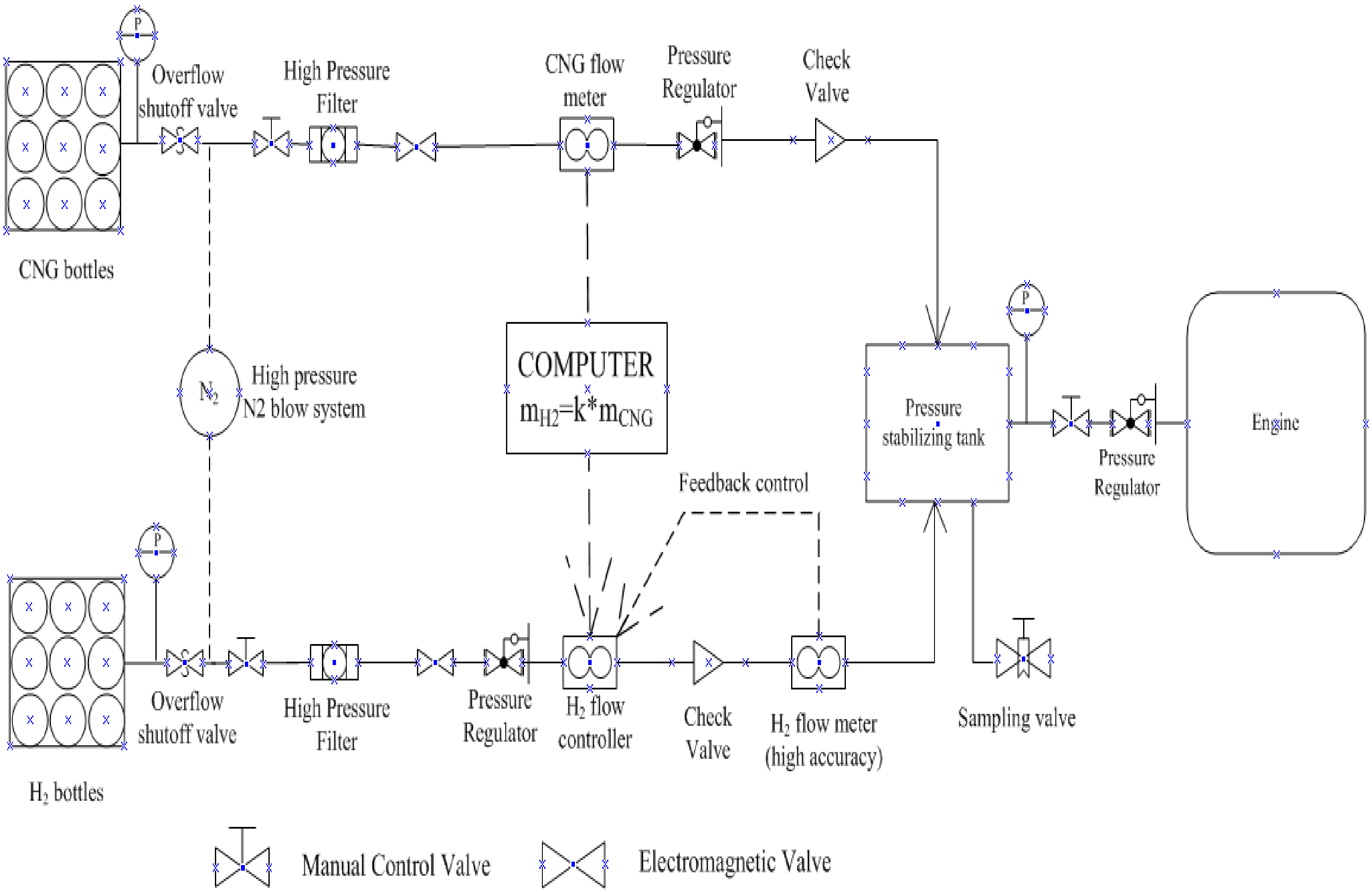
Engine's Structural Parameter and Performance

Type	EQD180N-30
Pattern	Four strokes、water-cooled、turbocharged and intercooled、single-point electronic control injection、ignition engine、Oxidation catalyst
Cylinder diameter ×stroke	105mm×120mm
Compression ration	10：1
Displacement	6.234L
Fuel	CNG
Ignition	high-energy free distributor electric control
Combustion Form	Lean burn
Rated power	132kW/2800r/min
Maximum torque	540N.m/1400r/min
Lowest full-load fuel consumption rate	225g/kW.h
Emission	Europe Ⅲ

Injected HCNG/CNG Supply System

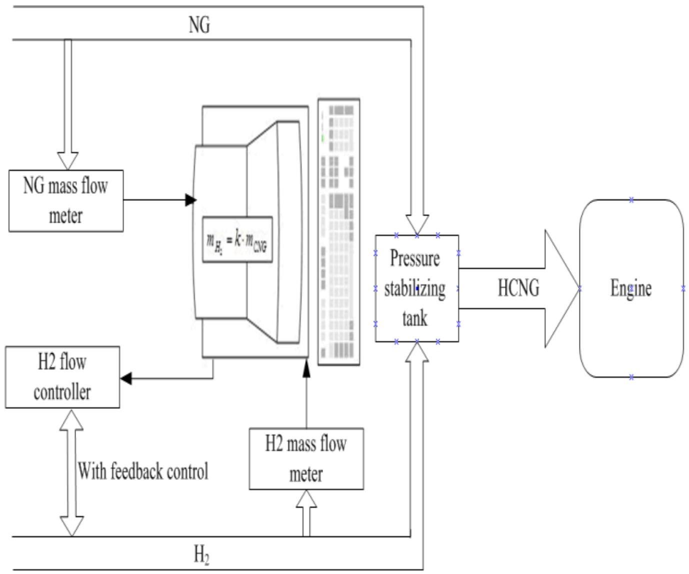


Schematic of the fuel supply system



Schematic of the on-line hydrogen- natural gas mixing system used

Principles of HCNG on-line mixing system

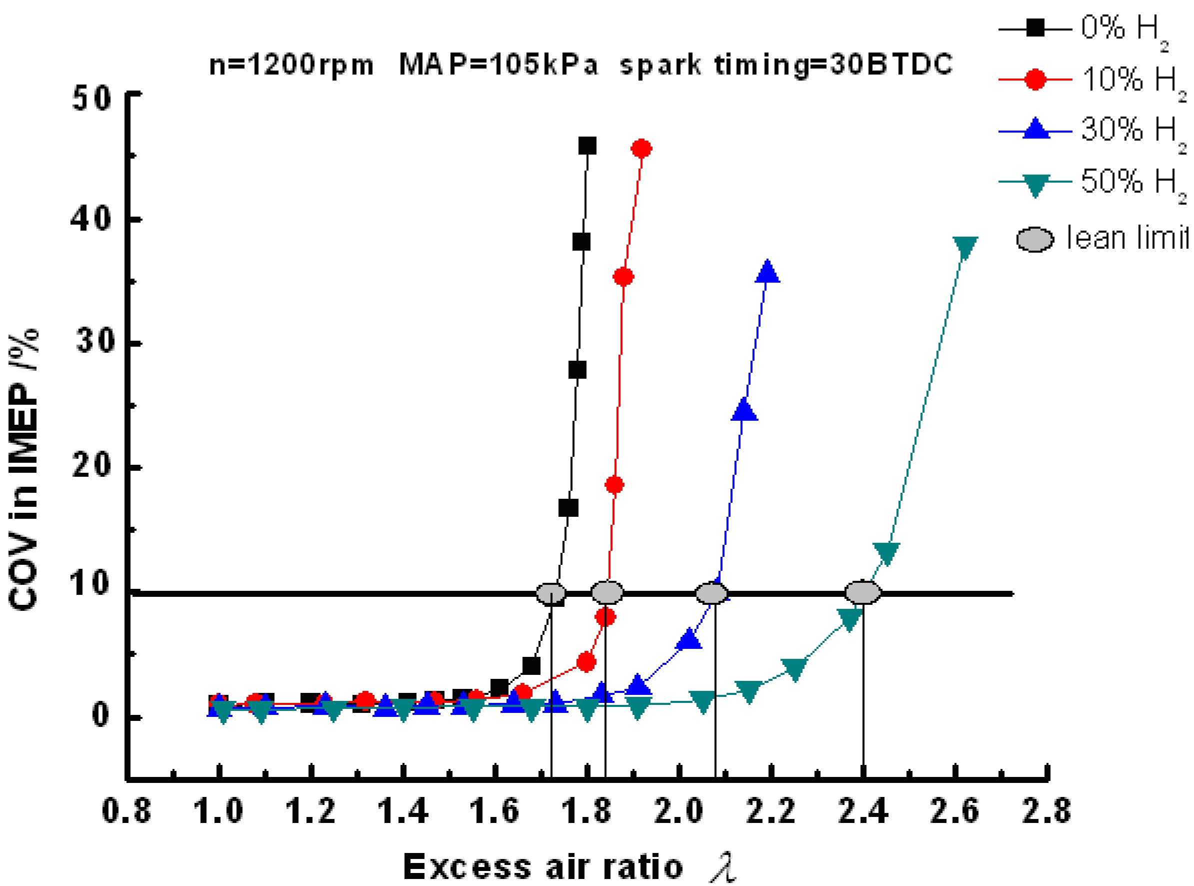


At first the measured NG mass flow rate is converted to an analog voltage signal which is then transferred to a computer for further processing after A/D converting. By using the stocked control software and the input value of blending ratio as well as the received signal of NG mass flow rate, the computer then calculates out the desired hydrogen mass flow rate.

This calculated value is used as an immediate input into the hydrogen flow controller, which controls the flow rate according to the desired value through varying the openness of the integrated valve. This resulted hydrogen flow rate need to be re-checked by a high accuracy mass flow meter located downstream the flow controller. If significant difference between the measured hydrogen flow rate and previously calculated one is found, a feedback control would become active to ensure control accuracy.

掺氢对稀燃极限的影响
Effect of Hydrogen Addition on Lean Operation Limit

COVIMEP



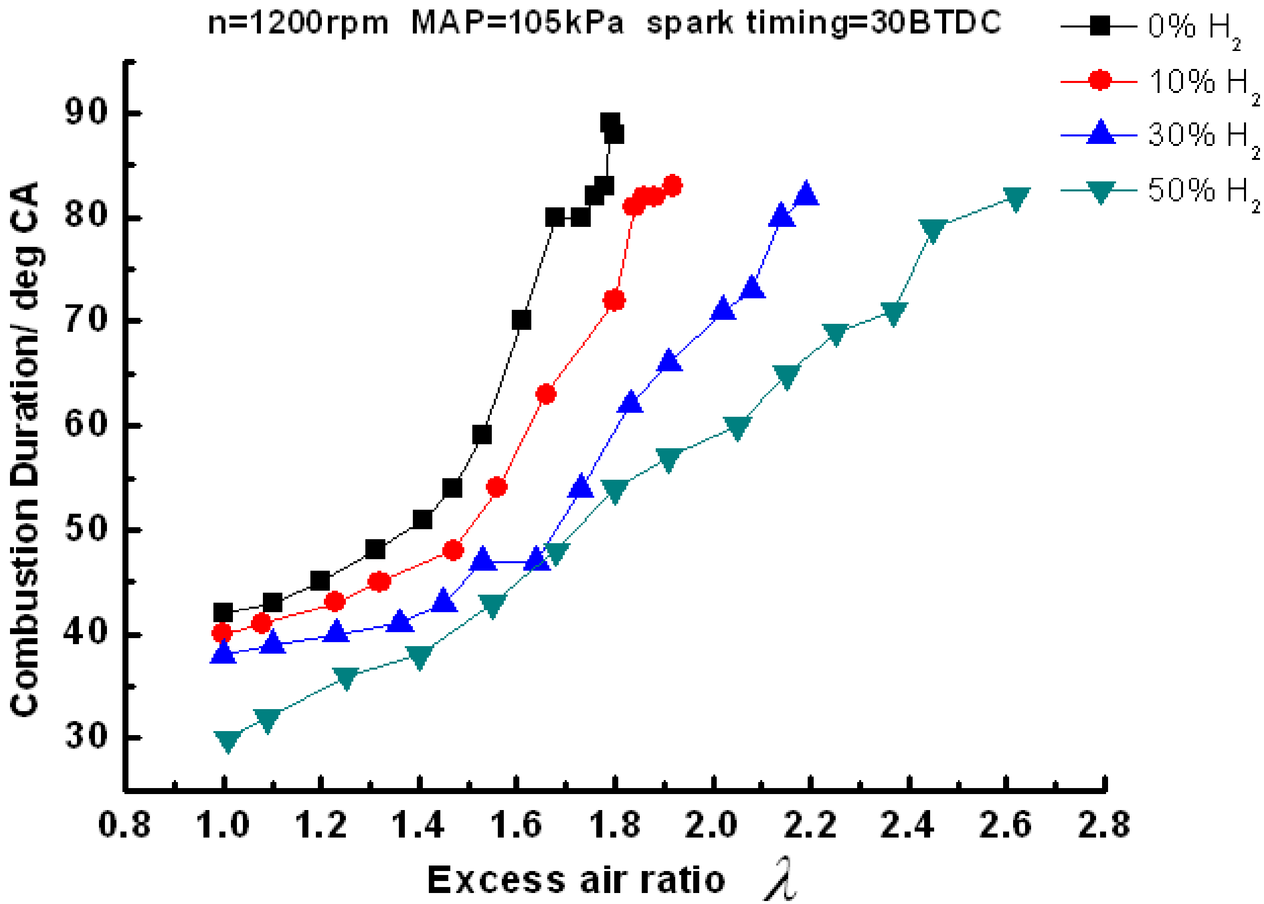
稀燃极限定义为平均指示压力的循环变动达到**10%**时的过量空气系数

The lean operation limit was defined as the excess air ratio at which COVIMEP reaches 10%.

掺氢比的提高可以拓宽稀燃极限，改善发动机的稀燃性能。

Hydrogen enrichment could significantly extend the lean operation limit, improve the engine’s lean burn ability.

燃烧持续期　　Combustion Duration

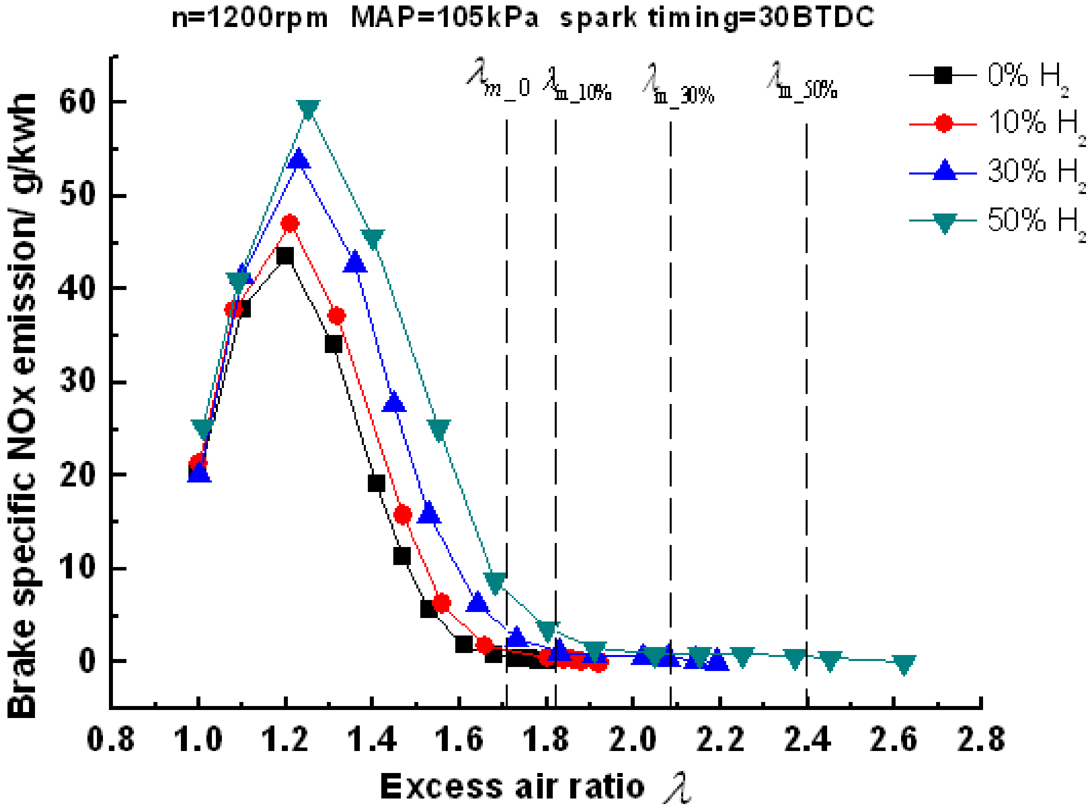


在空燃比确定的情况下，随着掺氢比的提高，燃烧持续期会缩短。这表明，掺氢确实可以提高火焰传播速度。

At a given lambda, combustion duration shortened as hydrogen fraction increased. This illustrated that hydrogen addition could indeed speed up flame propagation.

发动机热效率和排放特性

Engine Thermal Efficiency and Emission Characteristics



At fixed ignition timing

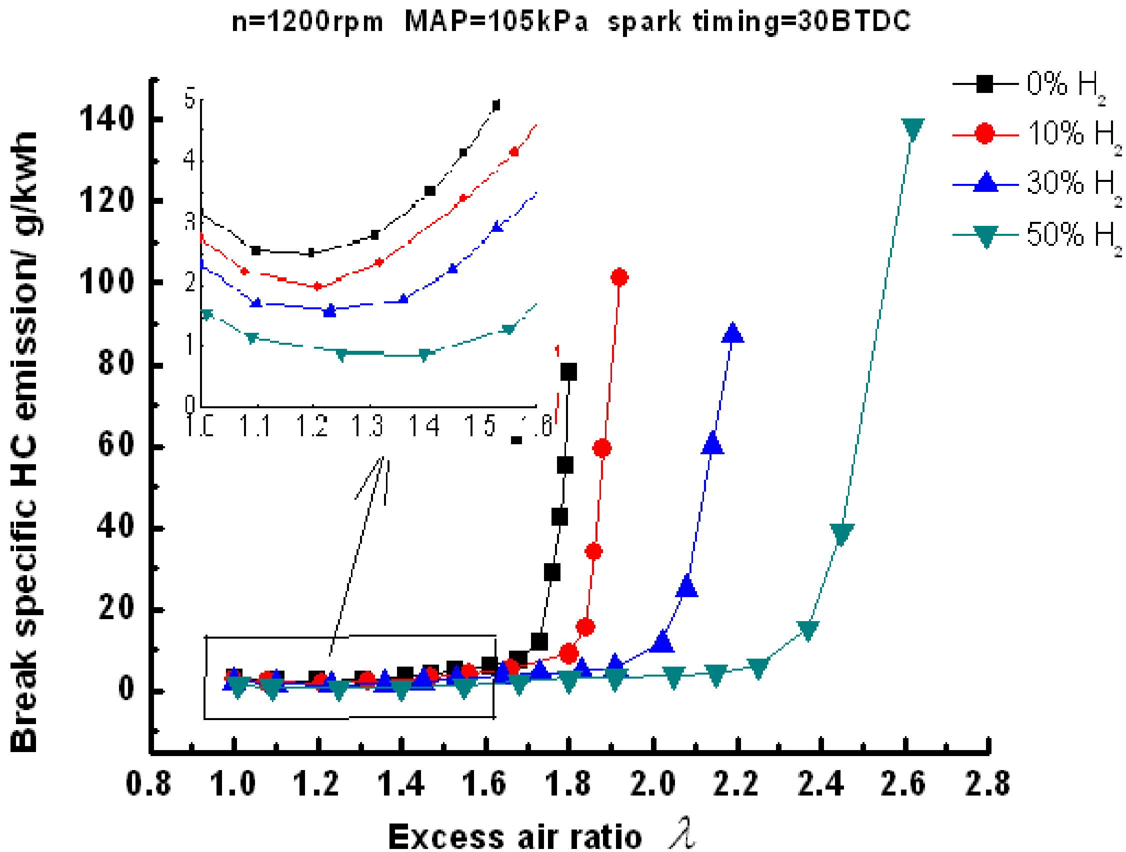
NOx

图中**λm_0**和**λm_10%** 分别表示**CNG**和掺氢比为**10%**的**HCNG**的稀燃极限。

λm_0 and λm_10% in these figures represent lean limit for NG and 10% hydrogen fraction mixture respectively.

同一空燃比下，掺氢比越高，**NOx**排放量越大。这是因为氢气的加入提高了燃烧温度，而高温是**NOx**形成的主要因素。

More hydrogen added would result in more NOx emission at a given lambda, this is thought to be caused by the elevated combustion temperature due to hydrogen addition since high temperature was a catalyst for the formation of NOx

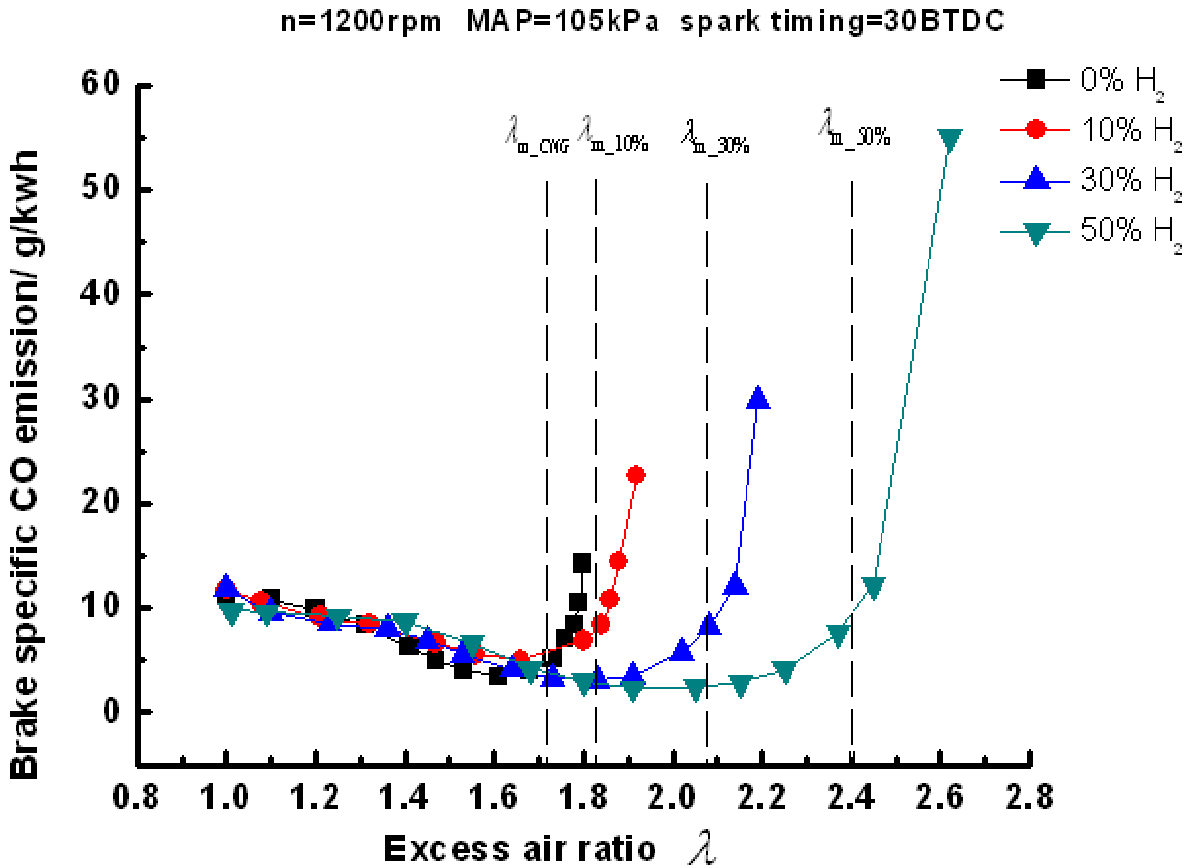


HC

由上图可看出，掺氢可降低HC的排放，这是因为氢气可以提高火焰传播速度，减小淬熄距离，从而降低了不完全燃烧的可能性。C浓度由于氢气的加入而有所降低也是HC排放下降的一个原因。

Reduced HC emission by hydrogen enrichment was observed in our study which could be explained by the fact that hydrogen could speed up flame propagation and reduce quenching distance, thus decreasing the possibilities of incomplete combustion . Carbon concentration of the fuel decreased due to hydrogen addition was another reason for HC emission reduction.

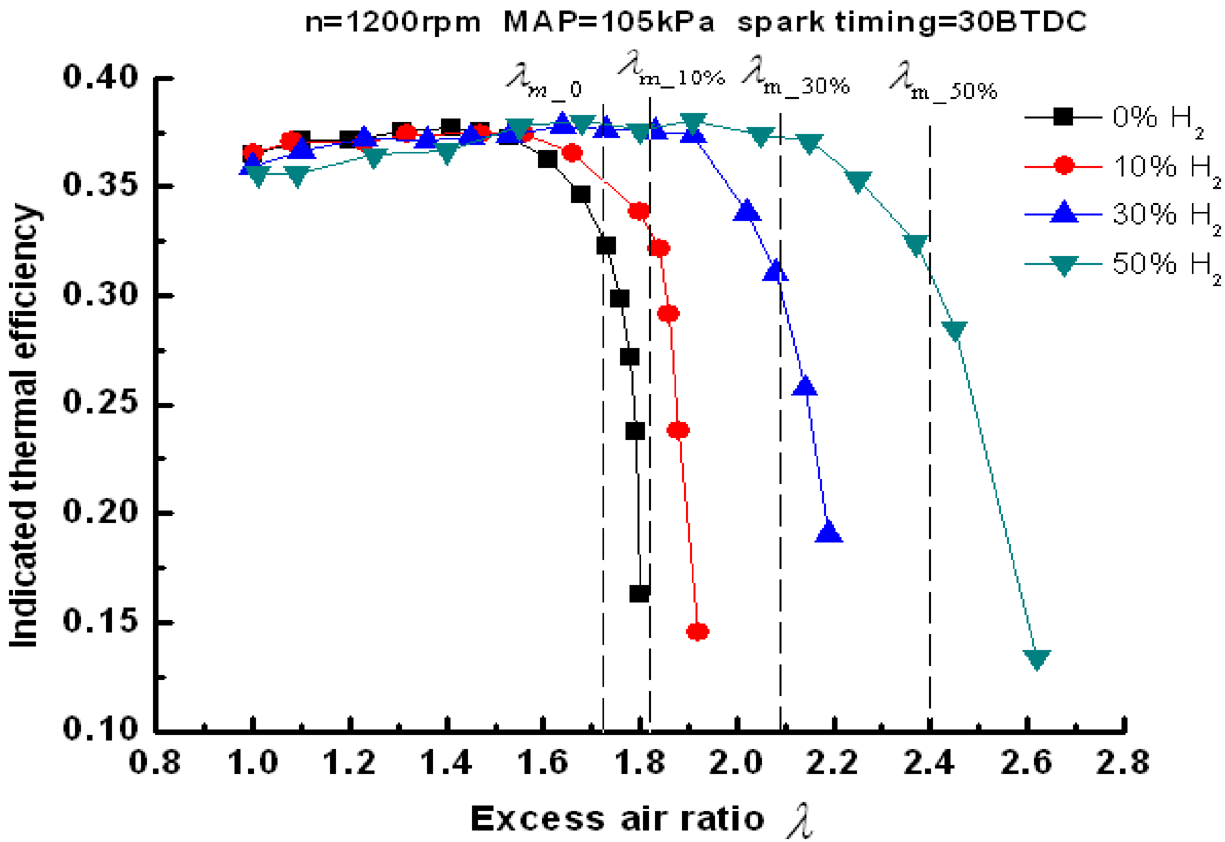
CO



在过量空气系数小于**1.7**的区域，掺氢与否对于**CO**排放的影响不明显，但一旦过量空气系数超过**1.7**，掺氢越多，**CO**排放越低。 这归功于氢气良好的燃烧特性，特别是在稀燃料的情况下。

In the region where lambda was less than 1.7, adding hydrogen or not showed no significant difference on CO emission, but once lambda exceeded 1.7, more hydrogen addition resulted in much less exhaust CO. This was also attributed to hydrogen’s ability to strengthen combustion, especially for lean fuel-air mixtures.

指示热效率　　Indicated Thermal Efficiency

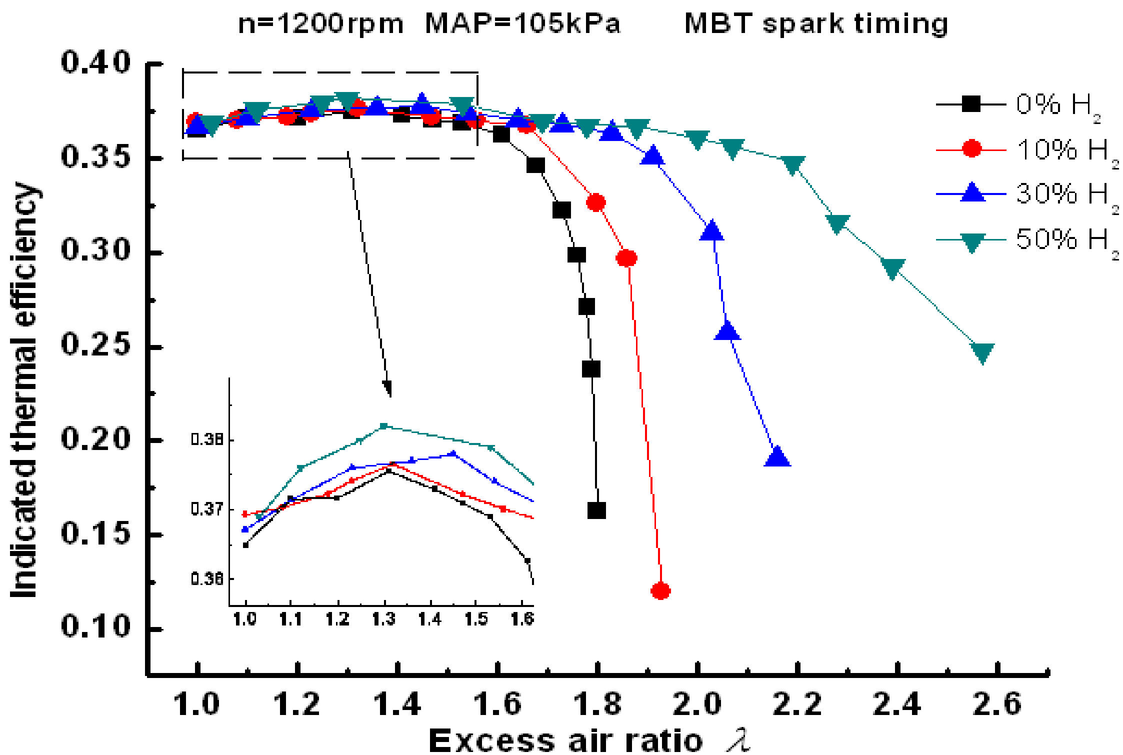


当过量空气系数小于**1.5**时，掺氢并没改善发动机的热效率，反而**50%**掺氢时的热效率与纯天然气发动机相比有明显的下降。

when lambda was under 1.5, hydrogen addition was not beneficial to engine’s efficiency improvement. Rather, the engine’s thermal efficiency exhibited an obvious drop when fuelled by HCNG containing 50% hydrogen compared to pure NG operation.

发动机的热效率和排放特性
Engine Thermal Efficiency and Emission Characteristics

At MBT

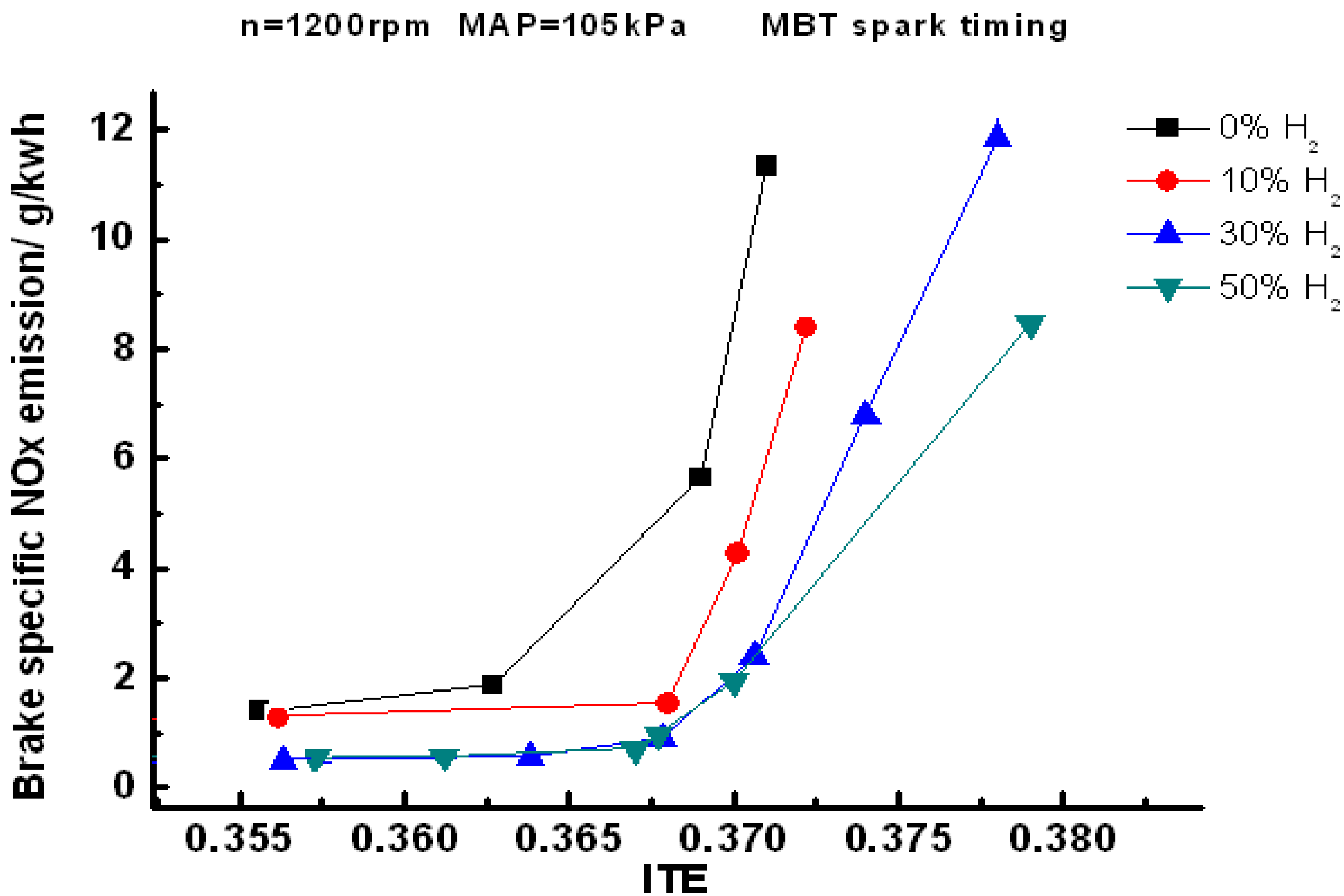


热效率

thermal efficiency

在最佳点火提前角处，掺氢可以提高发动机的热效率，高掺氢比有着更高的热效率。

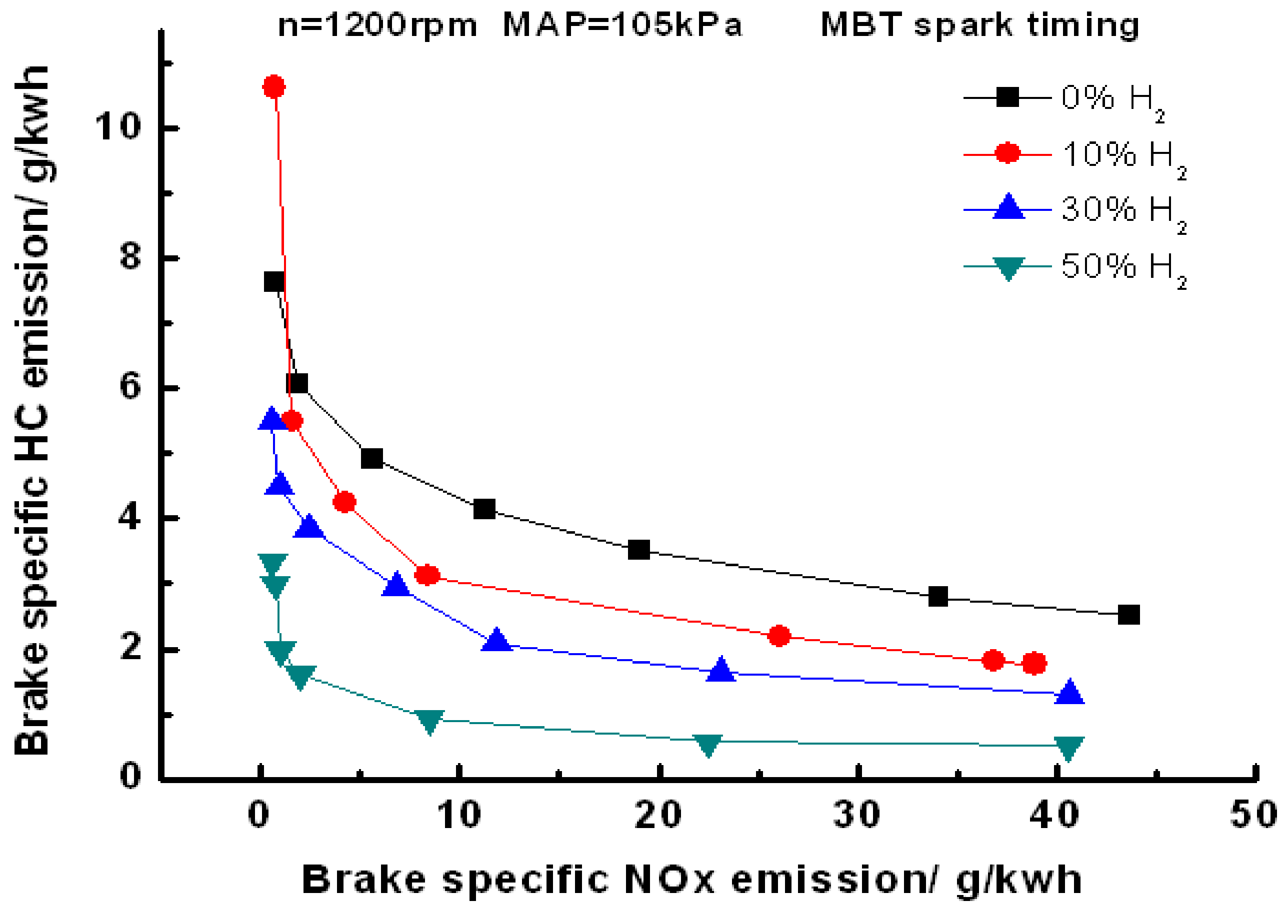
Hydrogen addition could improve thermal efficiency after spark timing optimization and that the more hydrogen added the more efficiency rise will be gained



NOx

相同指示热效率下，掺氢比增加可降低**NOx**排放。相同**NOx**排放下比较，掺氢越多，热效率越高。

At given ITE, NOx emission decreased as the increase of hydrogen fraction and at given NOx emission, ITE increased as more hydrogen is added.



掺氢比增加，**NOx**排放与**HC**排放相对曲线向左下角偏移，这说明了掺氢可降低**NOx**排放与**HC**排放相互矛盾的程度。

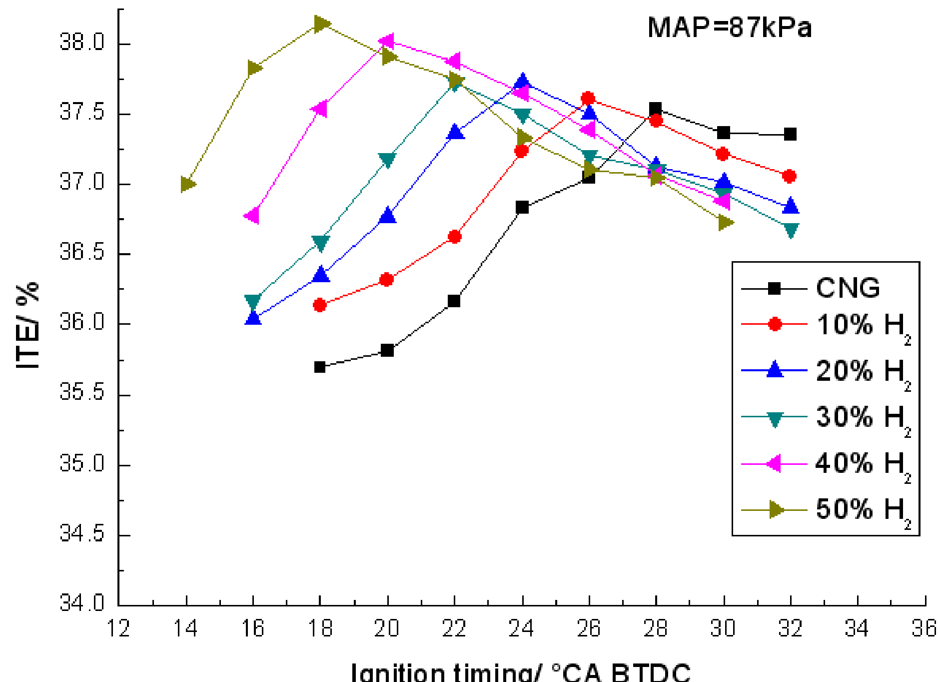
The trade-off curve moves further to the left-bottom as more hydrogen is added which meant that tradeoff between NOx and HC emission was indeed alleviated by hydrogen addition.

HCNG发动机在不同点火提前角下的燃烧和排放特性

Combustion and Emission Characteristics of a Port-Injection HCNG Engine under Various Ignition Timings

不同掺氢比下指示热效率与点火提前角的关系

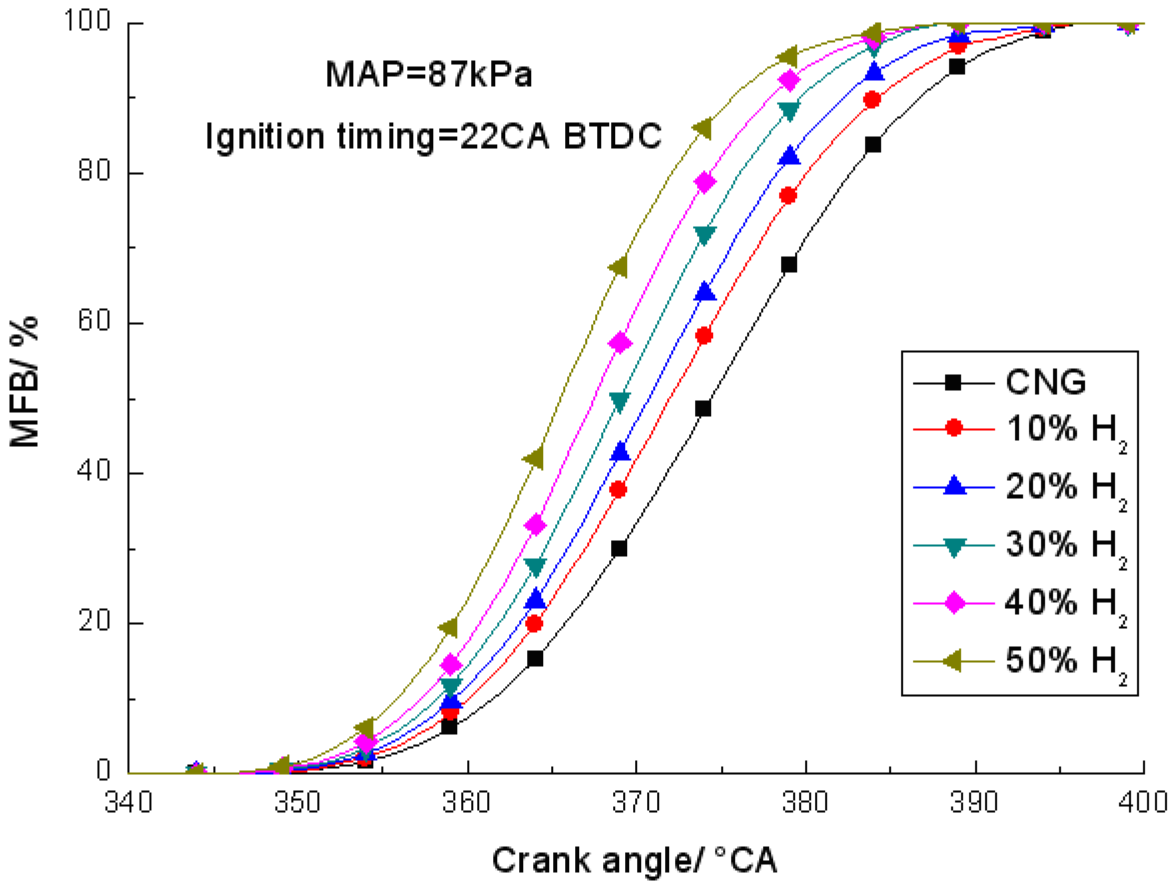
The Relationship between ITE and Ignition Timing at Various Hydrogen Fractions



最佳点火提前角随掺氢比增大而推迟，此外最佳点火提前角下的指示热效率随掺氢比增加有所提高。这是因为推迟点火可减小压缩负功，提高燃烧等容度，但传热损失量会因掺氢导致的缸内温度提高而增大。

The MBT is retarded as the hydrogen blend ratio is raised; furthermore the ITE at the MBT rises slightly. This is because retarding ignition timing can reduce the compression minus work, increase the constant volume degree, but the heat transfer can be raised by adding hydrogen to CHG due to the higher cylinder temperature

不同掺氢下的燃烧放热率曲线 MFB of the Fuel Blends

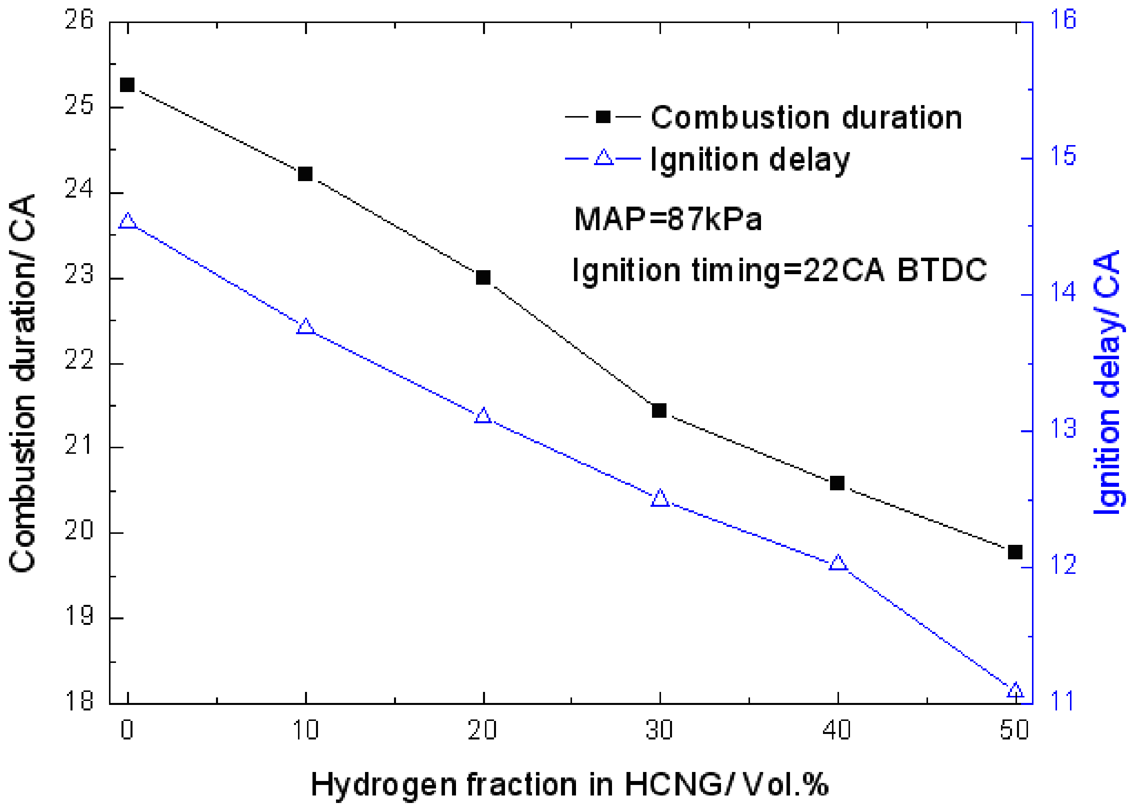


掺氢比增加燃烧放热会提前

The MFB is advanced as hydrogen addition increases.

不同掺氢比下的燃烧持续期和着火落后期

Combustion Duration and Ignition Delay versus Hydrogen Fractions

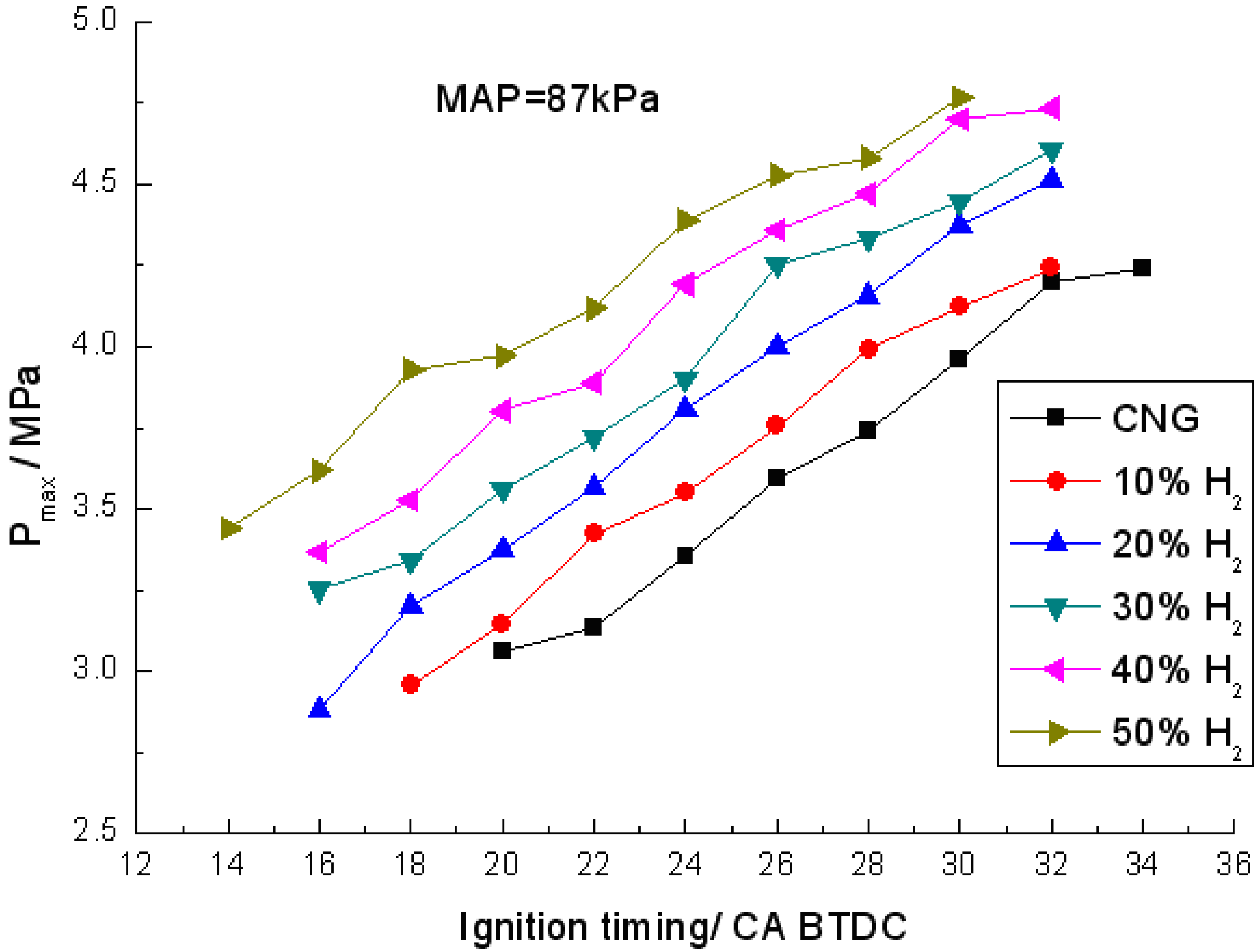


氢气百分数的增加会缩短快燃期，减少后燃期，同时提高燃料利用率。

The rapid combustion duration is shortened by increasing the hydrogen fraction which results in reducing in post-combustion and an increase in the rate of fuel utilization.

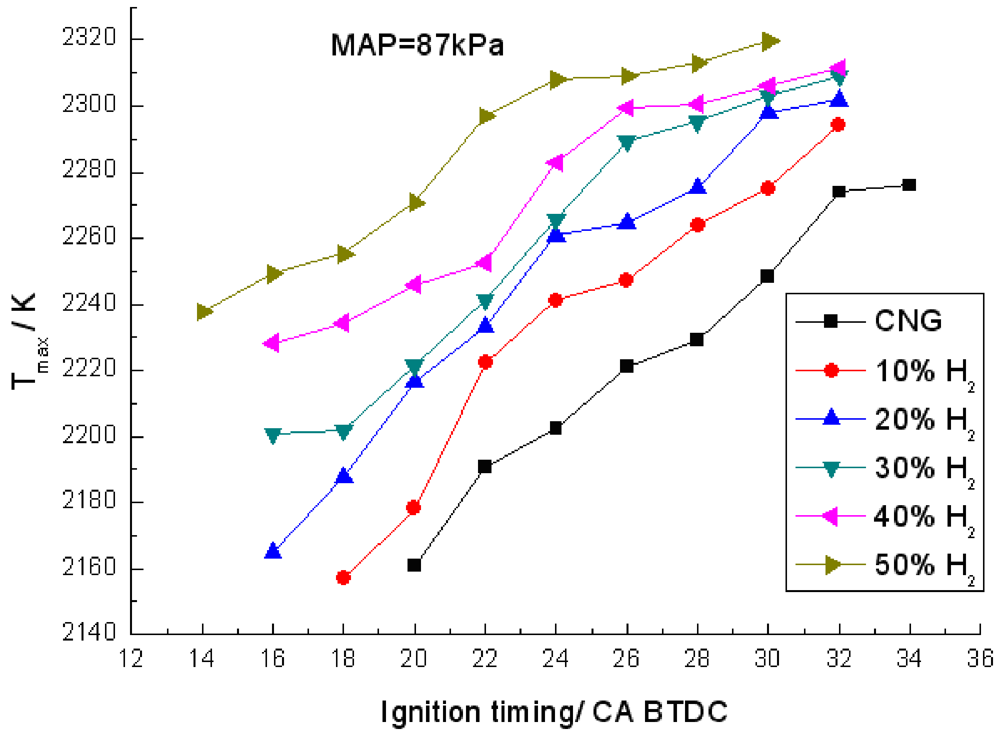
不同点火提前角下的缸内最高压力P_{max}

The Maximum Cylinder Pressure P_{max} versus Ignition Timings



不同点火提前角下的缸内最高温度T_{max}

The Maximum in-cylinder Gas Temperature T_{max} versus Ignition Timings

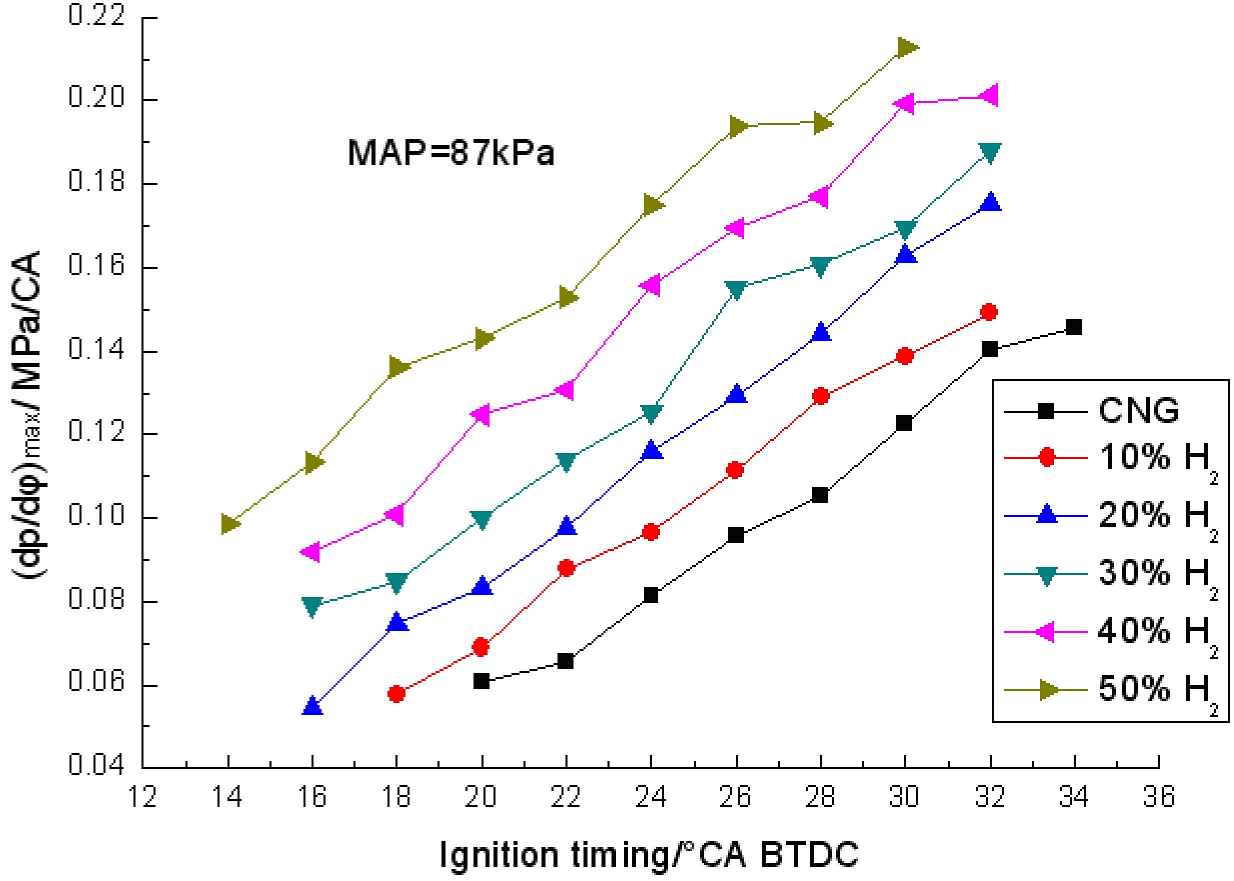


***P*max** 和 ***T*max** 随点火提前角的增大而有所提高，同时随着氢气含量的增加，因燃烧速率提高和压力的快速增高， ***P*max** 和 ***T*max** 也会随之增大。

*P*max and *T*max rise with the increase of spark advance angle, and also rise with raising the hydrogen fractions due to enhanced burning velocity, and quickly elevated pressure

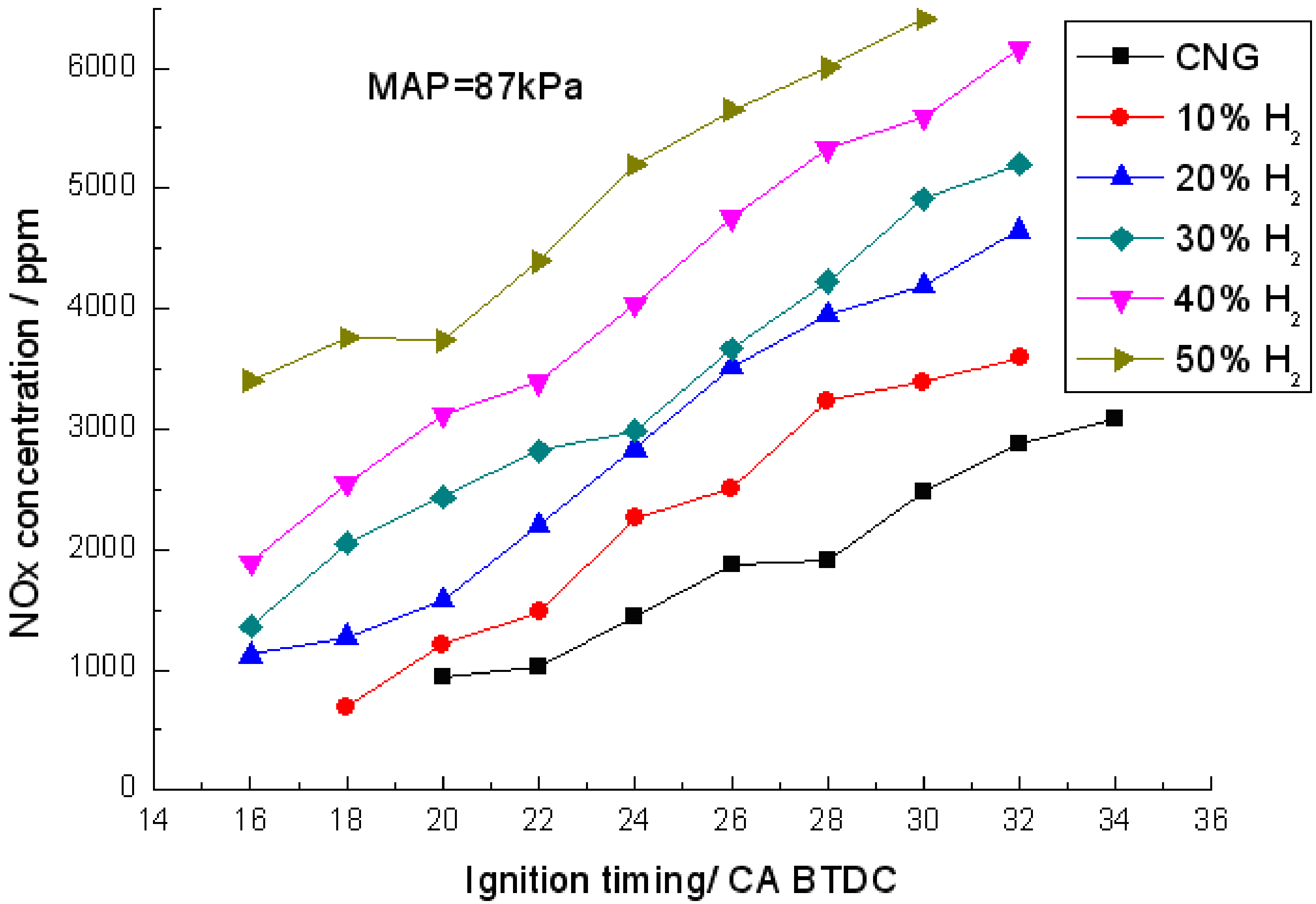
不同掺氢比下最大压力升高率与点火提前角的关系

Maximum rate of pressure rise of the fuel blends versus ignition timings



NOx 排放与点火提前角的关系

NOx Concentration versus Ignition Timings

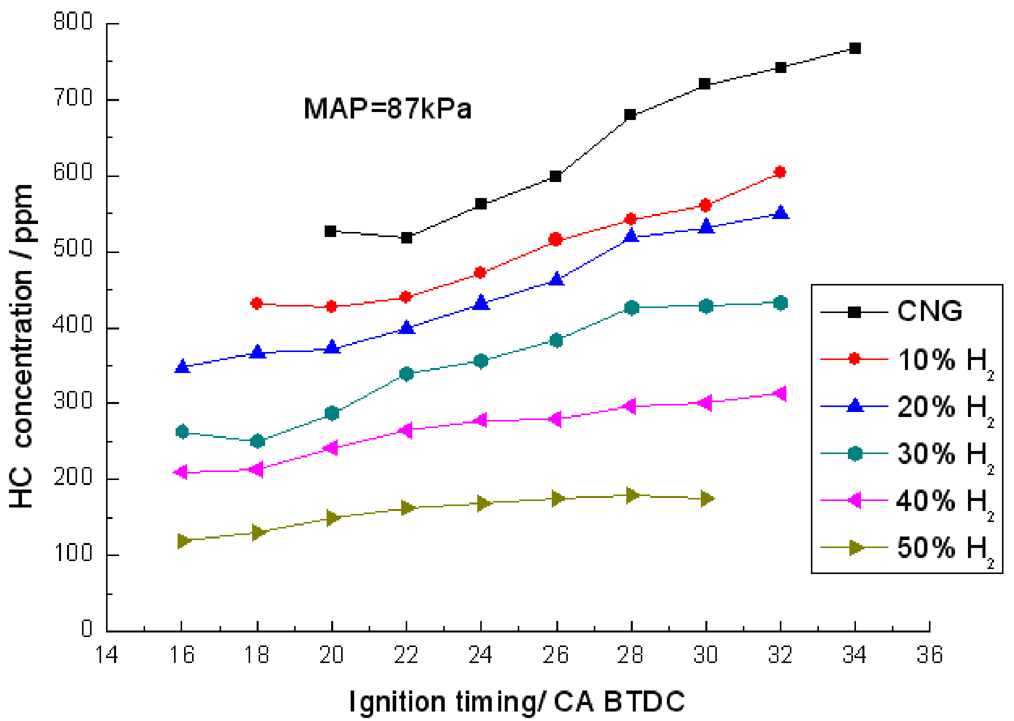


点火提前角和掺氢比的增加都会使得**NOx**排放量有所增加。

The NOx emission rises with the increase of spark advance angle, as well as with the increase of hydrogen fractions.

不同掺氢比下HC排放与点火提前角的关系

HC Emission versus Ignition Timing at Various Hydrogen Fractions

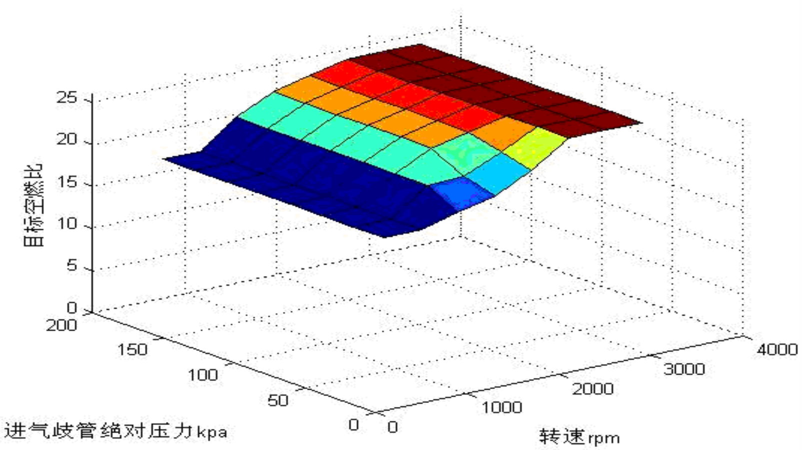


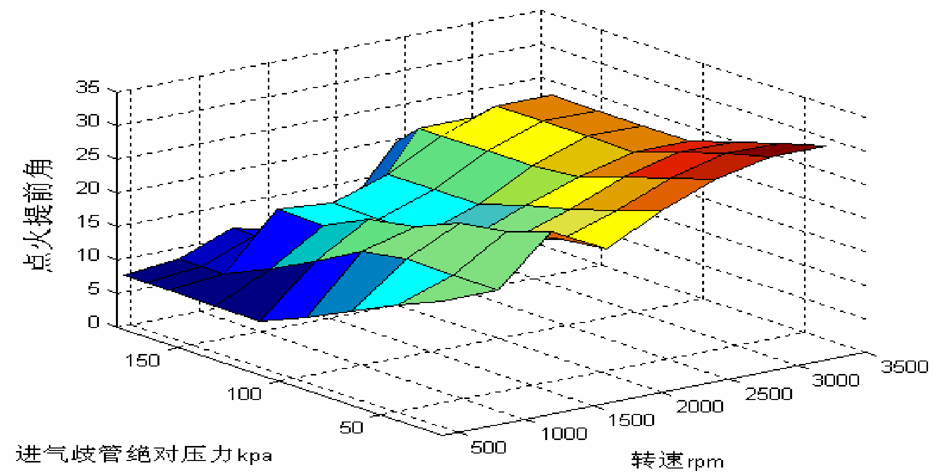
点火提前角减小会降低**HC**的排放，这是因为这时后燃期显得比较突出，尾气温度提高，这会加速**HC**在膨胀冲程和排气管内的燃烧。

HC emission falls by decreasing the spark advance angle, because post-combustion becomes serious and the emission temperature rises, which accelerates the combustion of the HC emission in the expand stroke and the exhaust pipe.

通过HCNG燃料空燃比调整特性试验的结果对比原机燃用天然气的MAP数据，优先选择在扭矩相近的前提下NOx比排放降低的最大空燃比点作为目标空燃比,由此得出HCNG发动机的目标空燃比MAP图；在点火提前角的标定过程中，实际空燃比保持在HCNG发动机的目标空燃比，在保持动力性不变的前提下尽量推迟点火，以降低NOX排放，最终得到的点火提前角MAP图。

The calibrated air-fuel ratio and spark timing map were achieved based on the goals of the emission (especialy NOx), specific fuel consumption and power output of the HCNG engine.





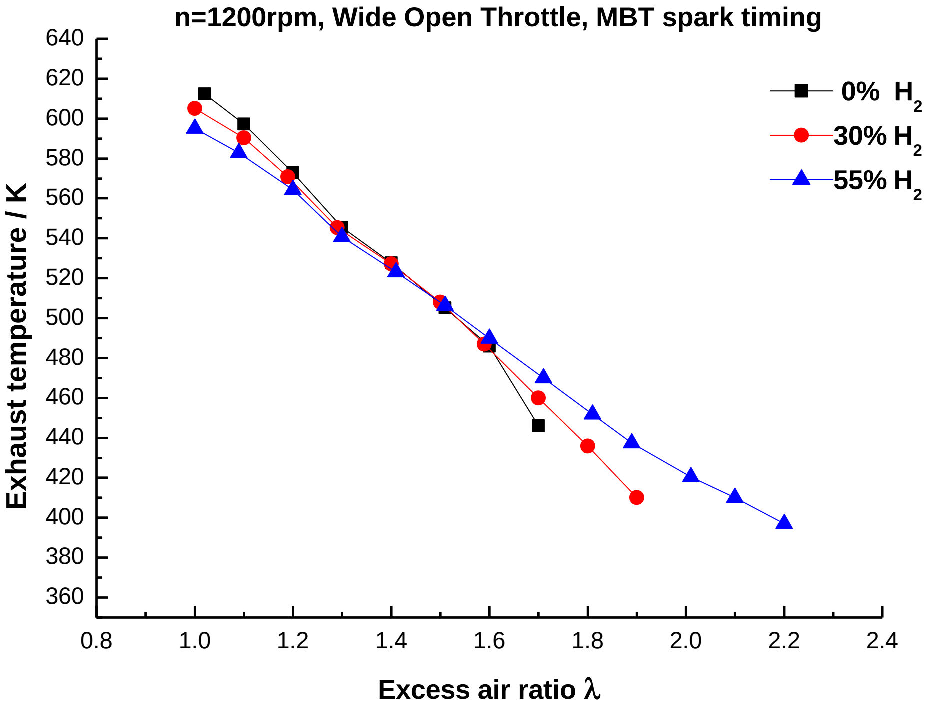
HCNG (20% H2) Engine Emission Data

	欧Ⅳ限值 Euro data	欧Ⅴ限值 Euro Ⅴ data	EEV限值 EEV data	实测值 Measured data
NOx (g/kW.h)	3.5	2.0	2.0	1.18-1.60
CO (g/kW.h)	4.0	4.0	3.0	0.26-0.80
NMHC (g/kW.h)	0.55	0.55	0.40	0.09-0.20
CH4 (g/kW.h)	1.1	1.1	0.65	0.40-0.50

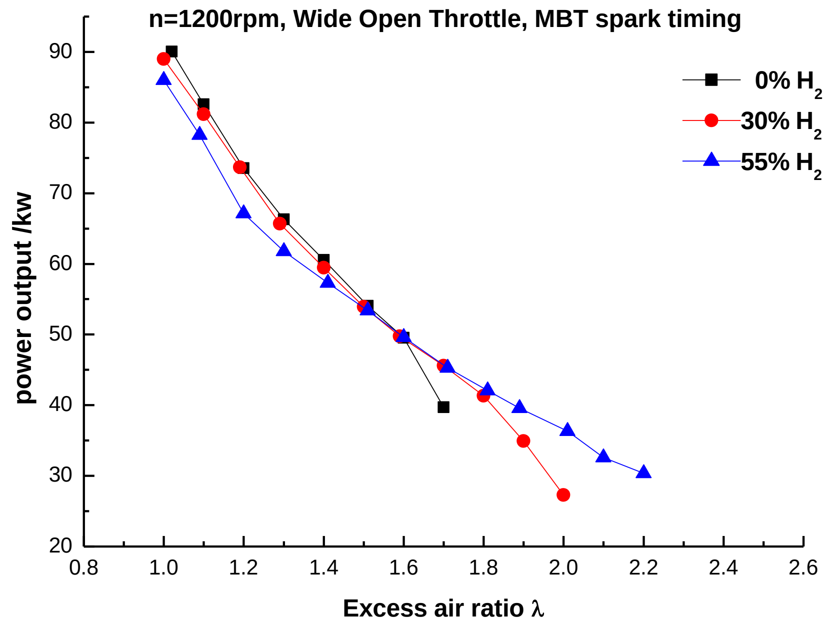
55%HCNG发动机燃烧和排放特性

Combustion and Emission Characteristics of a Port-Injection HCNG Engine fueled by 55% hydrogen volumetric ratio

Combustion and Emission Characteristics versus excess air ratio engine speed of 1200 rpm, Wide Open Throttle, MBT spark timing

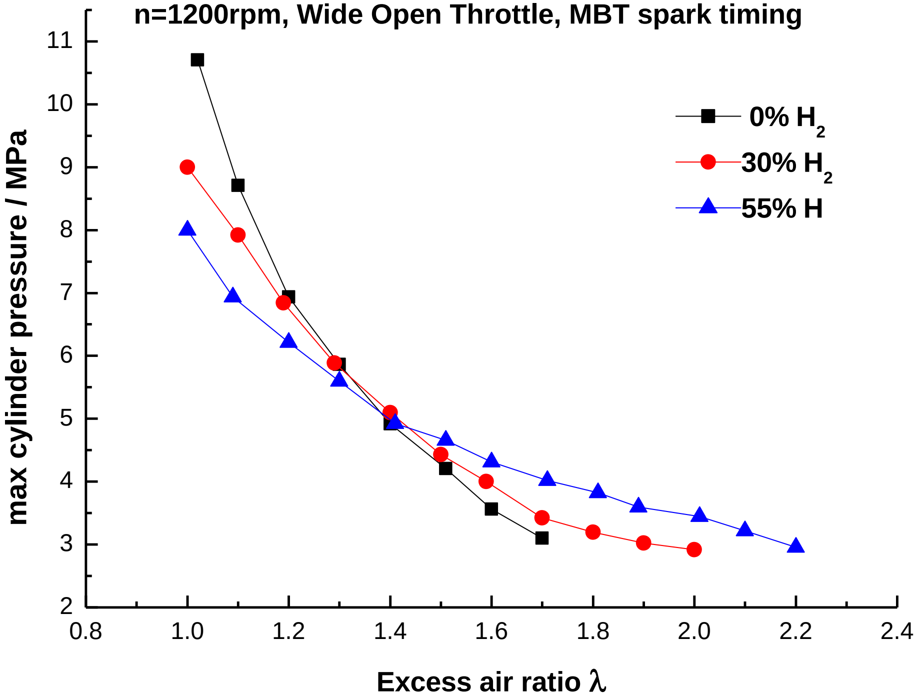


Exhaust temperatures versus excess air ratio

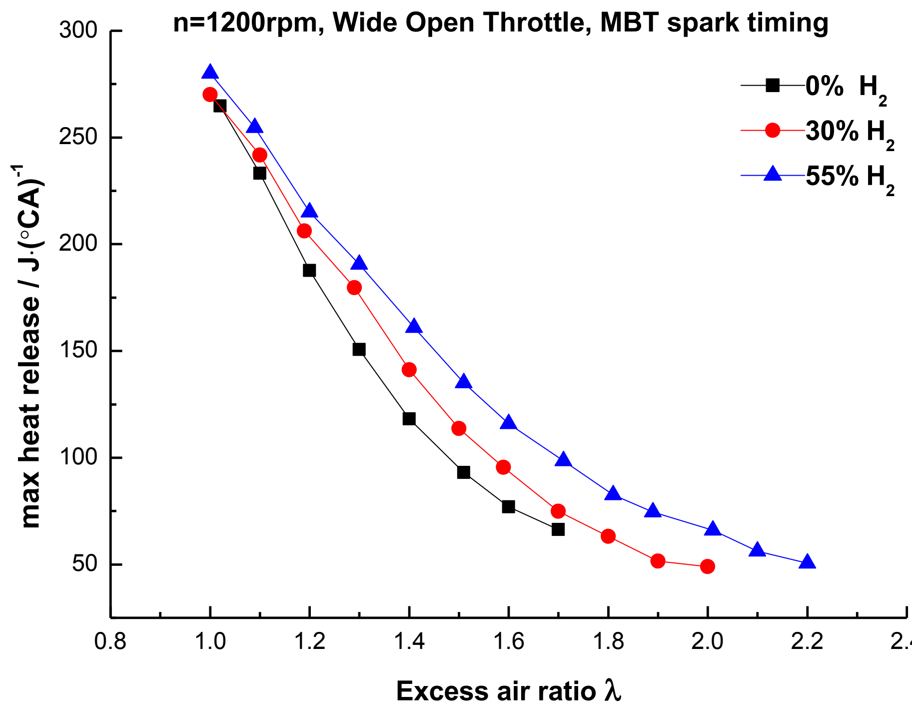


Engine's power performance versus excess air ratio

Combustion and Emission Characteristics versus excess air ratio engine speed of 1200 rpm, Wide Open Throttle, MBT spark timing

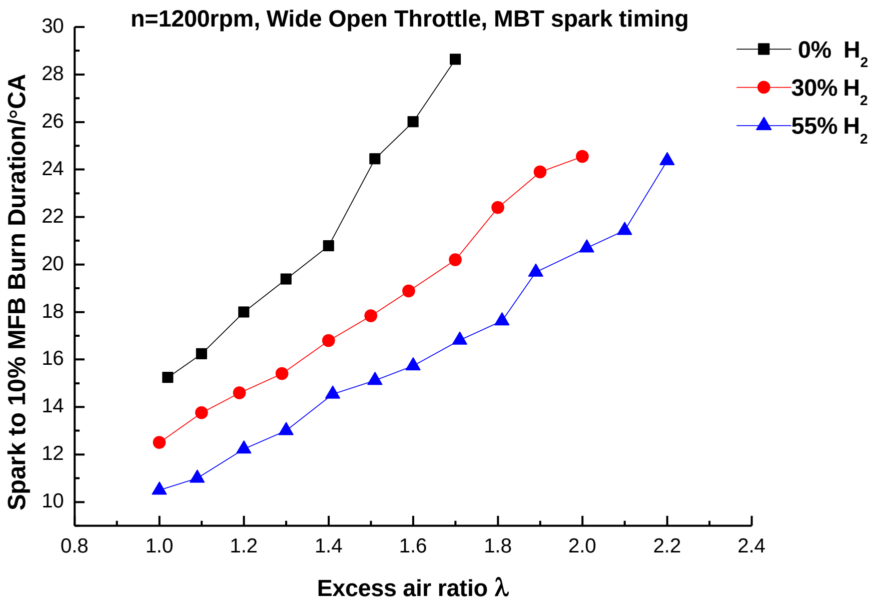


Max cylinder pressure versus excess air ratio

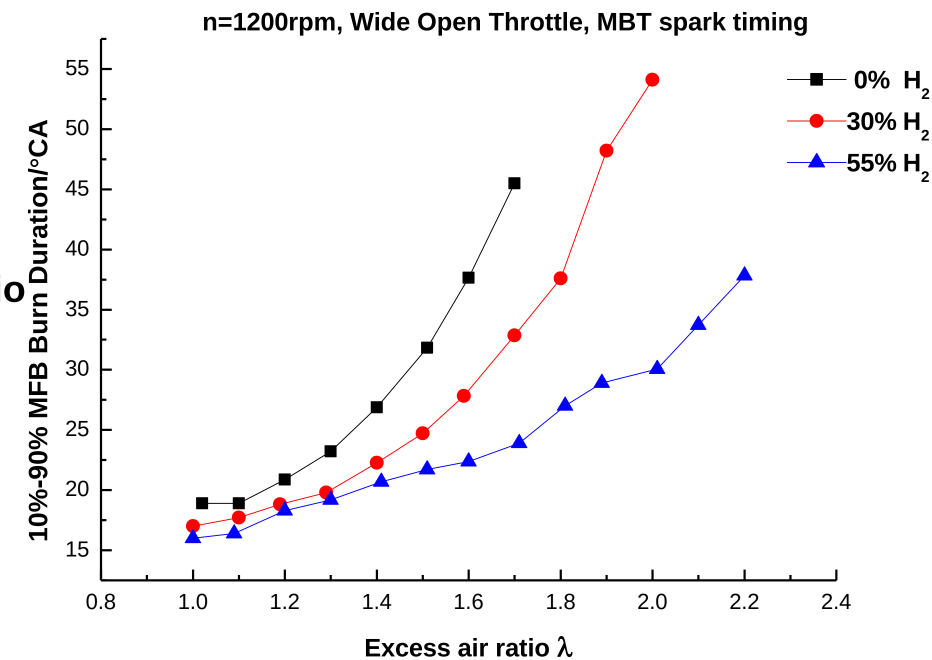


Max heat release rate versus excess air ratio

Combustion and Emission Characteristics versus excess air ratio engine speed of 1200 rpm, Wide Open Throttle, MBT spark timing

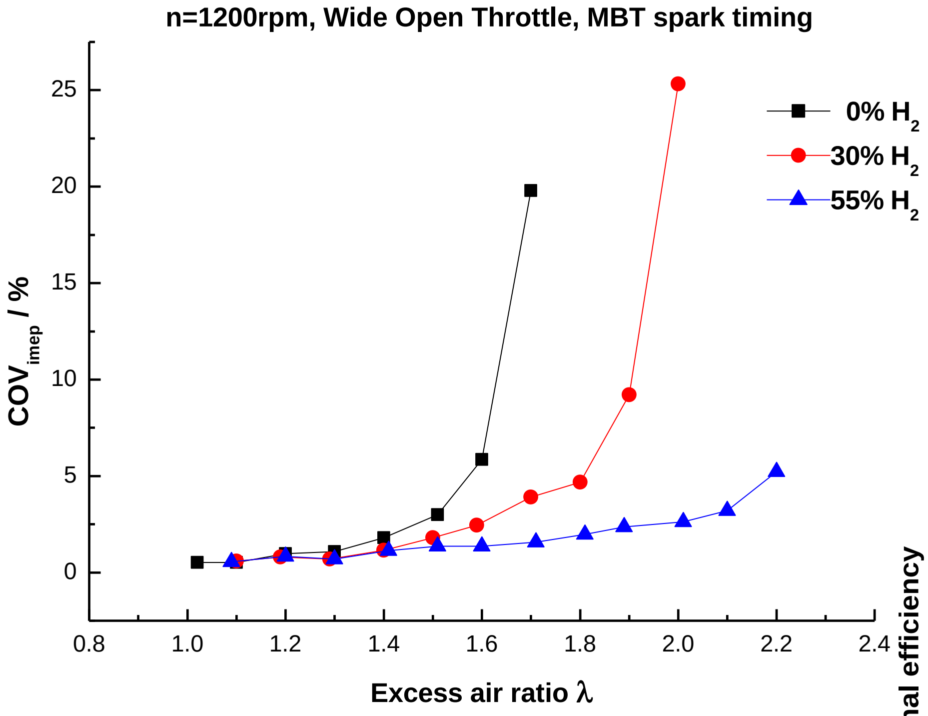


Spark to 10% MFB burn duration versus excess air ratio

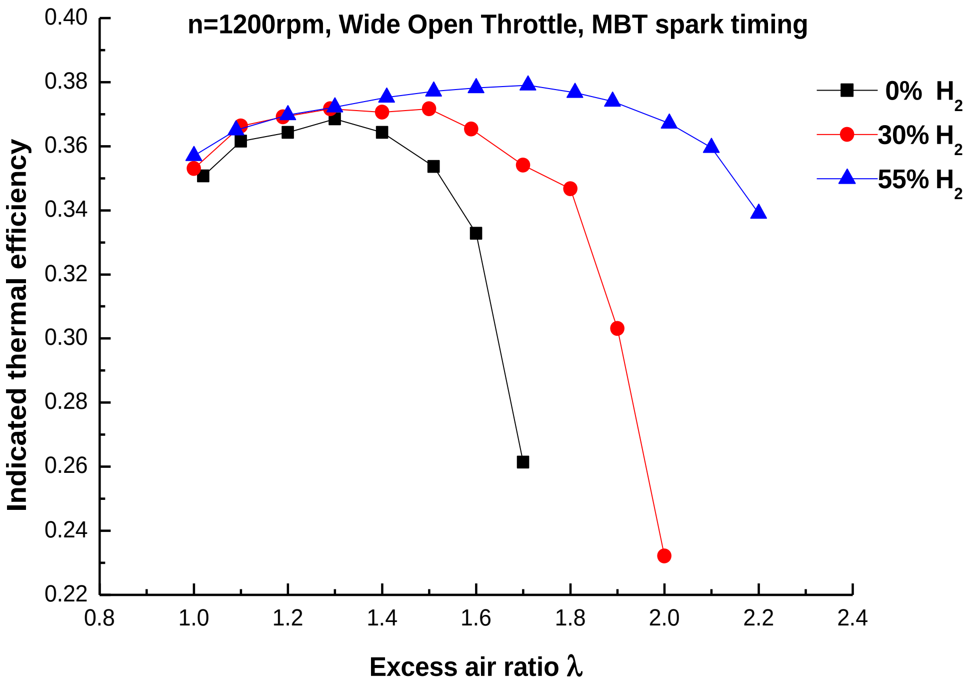


10% to 90% MFB burn duration versus excess air ratio

Combustion and Emission Characteristics versus excess air ratio engine speed of 1200 rpm, Wide Open Throttle, MBT spark timing

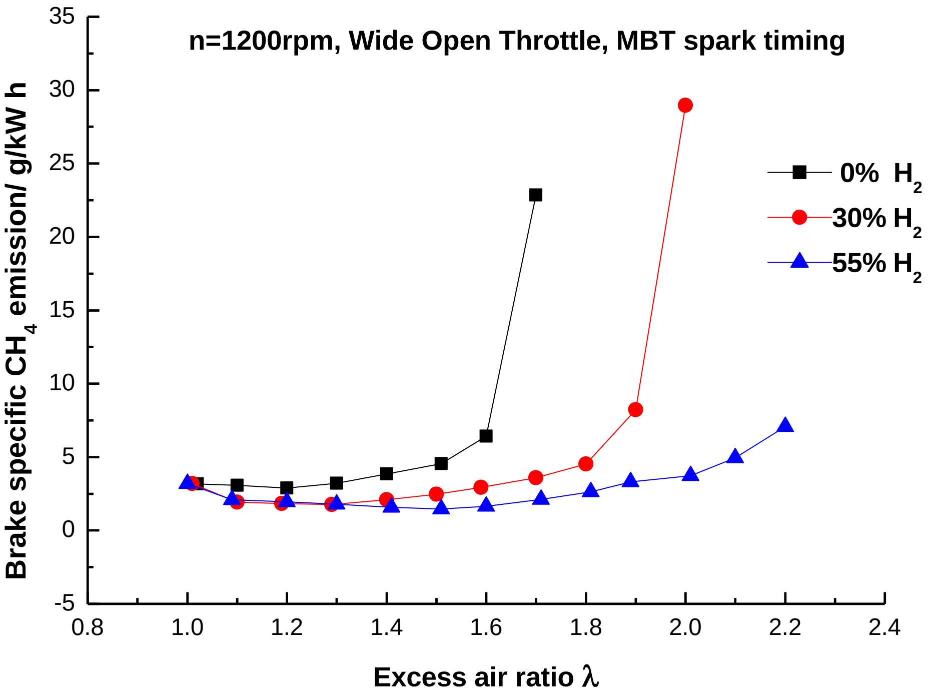


COV_{imep} versus excess air ratio

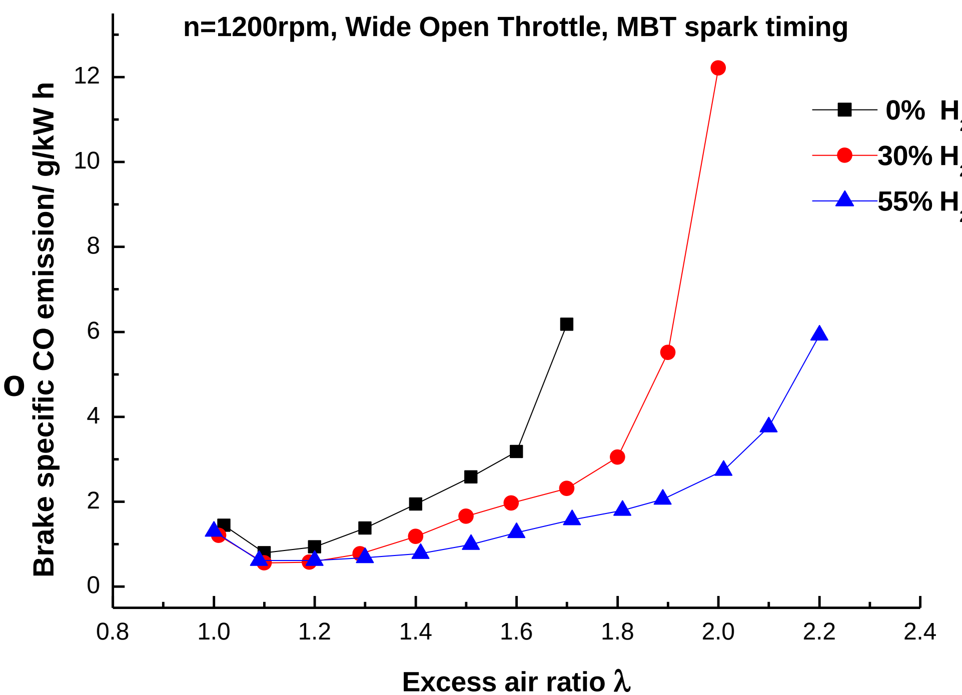


Indicated thermal efficiency versus excess air ratio

Combustion and Emission Characteristics versus excess air ratio engine speed of 1200 rpm, Wide Open Throttle, MBT spark timing

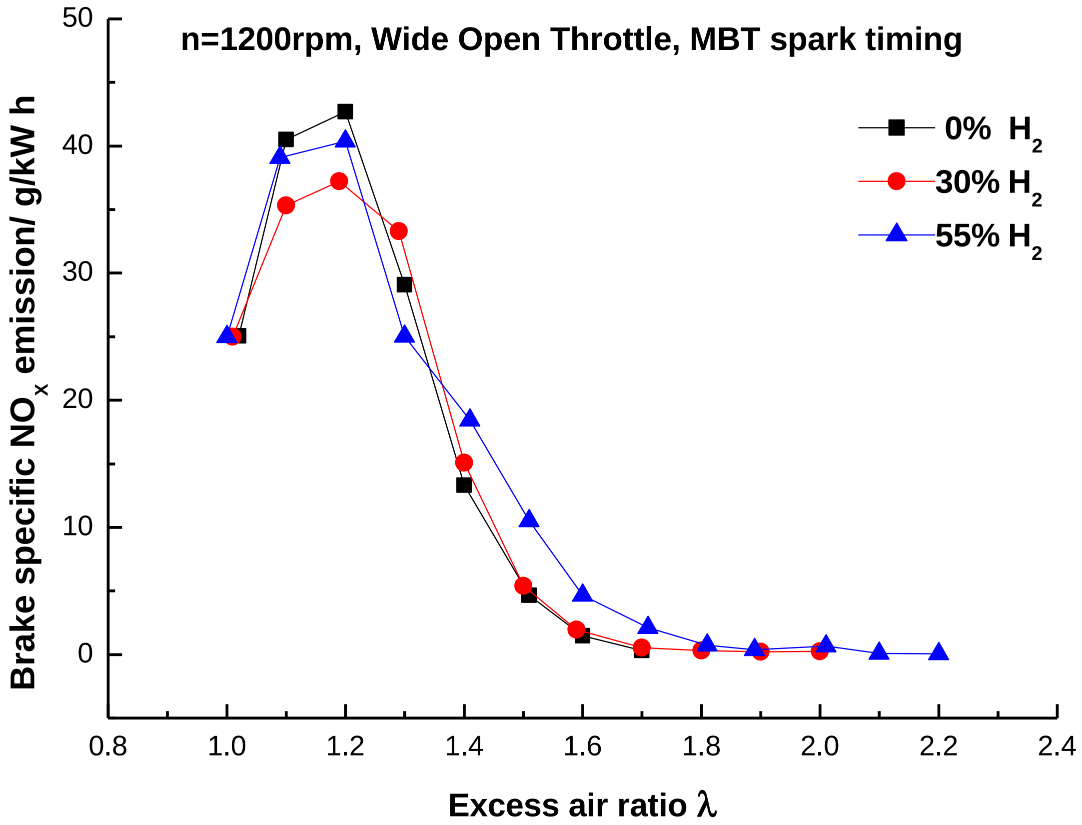


Brake specific CH4 emission versus excess air ratio



Brake specific CO emission versus excess air ratio

Combustion and Emission Characteristics versus excess air ratio engine speed of 1200 rpm, Wide Open Throttle, MBT spark timing

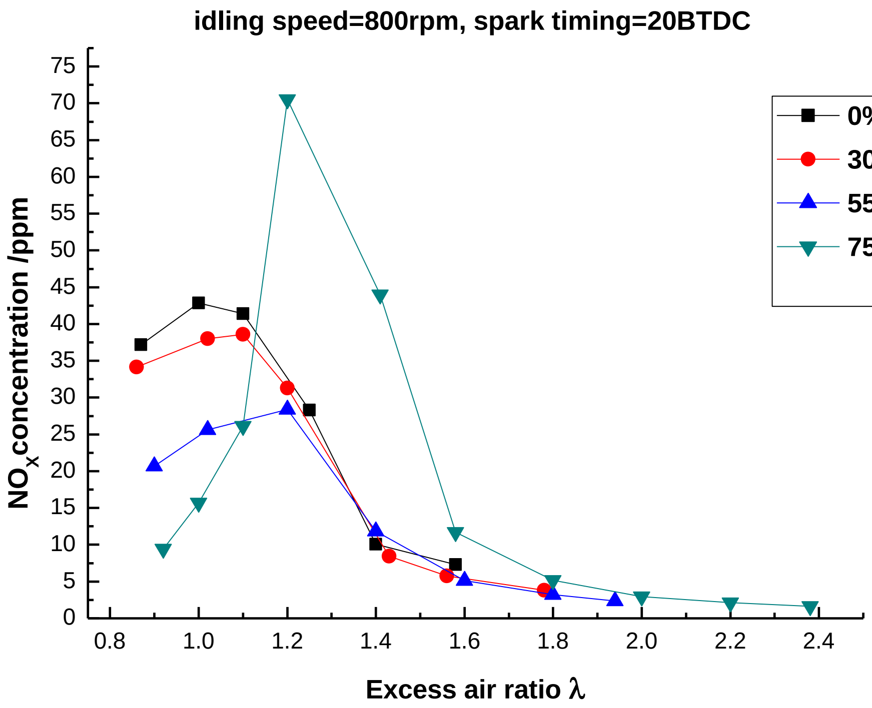


Brake specific NO_x emission versus excess air ratio

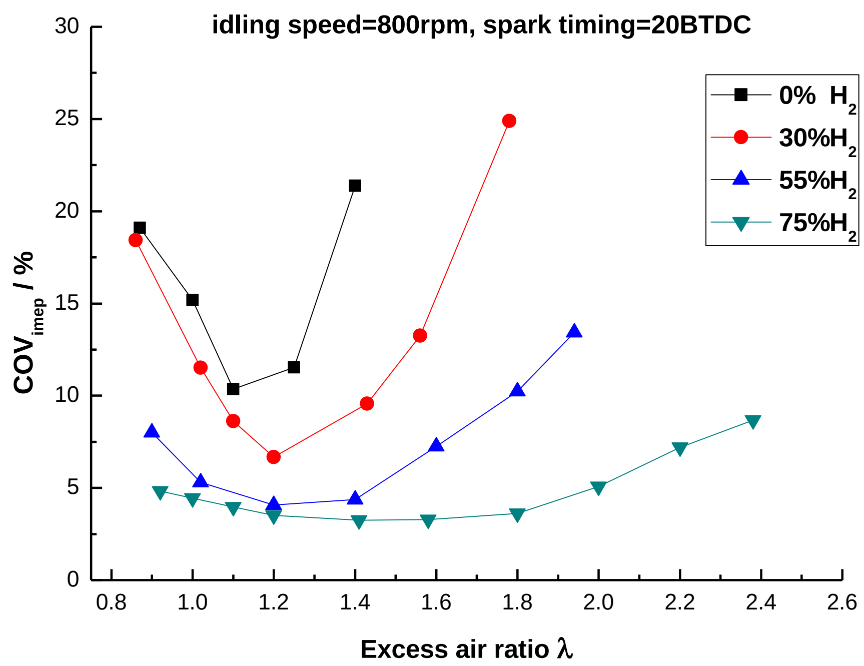
HCNG发动机怠速特性研究

Idle Characteristics of HCNG Engine

Idle Combustion and Emission Characteristics
idle speed=800rpm, spark timing=20BTDC

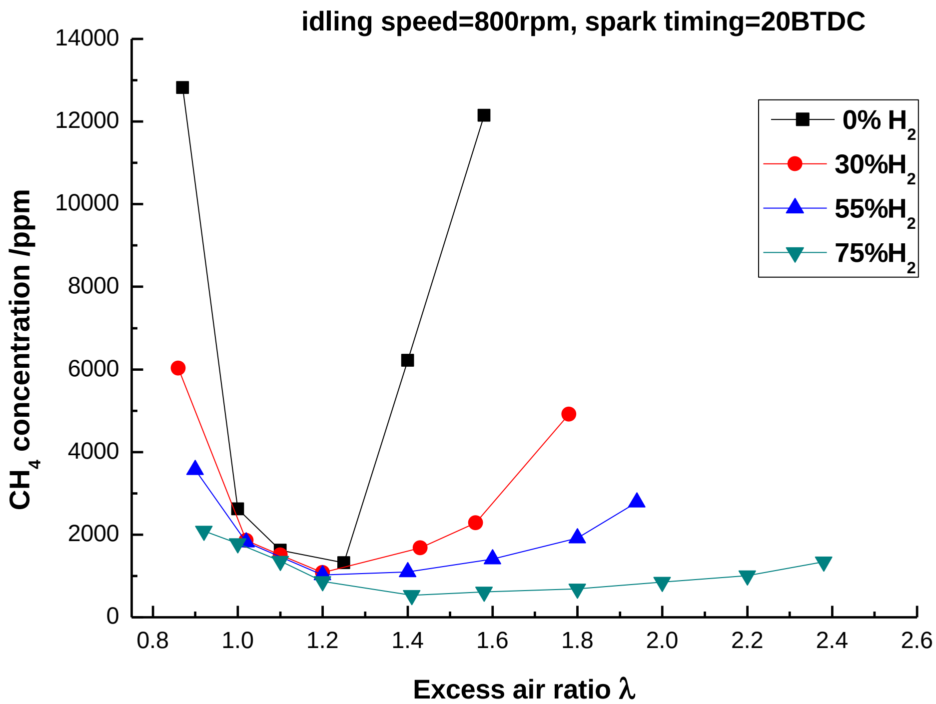


NO_x emission versus excess air ratio

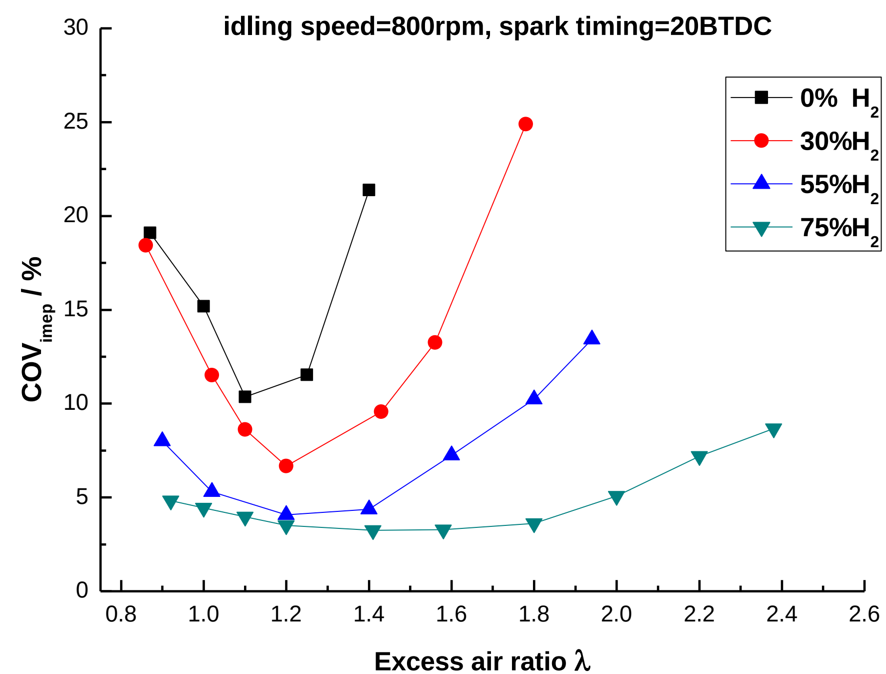


COV_{imep} versus excess air ratio

Idle Combustion and Emission Characteristics
idle speed=800rpm, spark timing=20BTDC

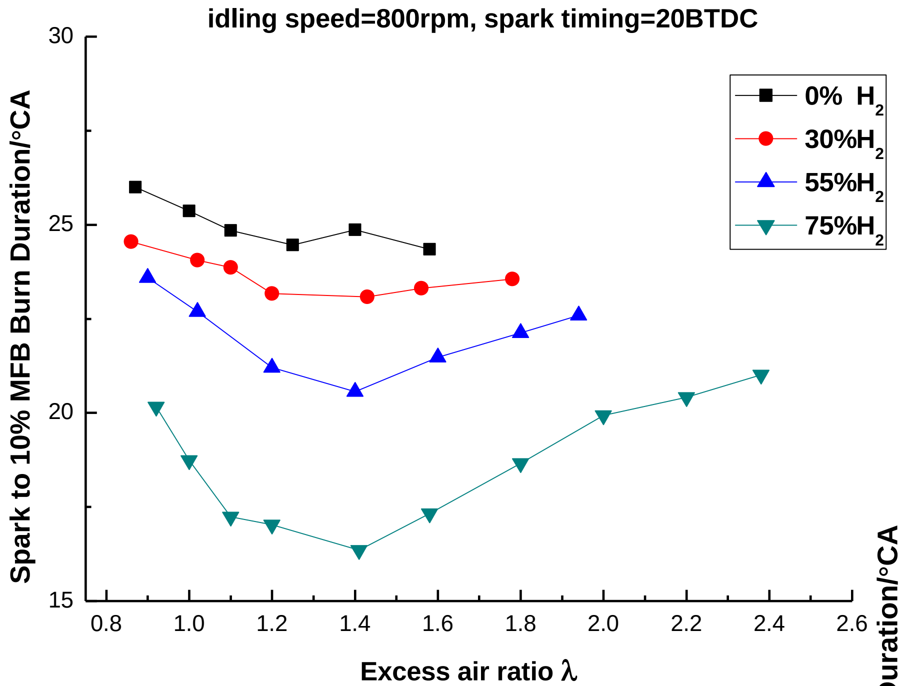


CH_4 emission versus excess air ratio

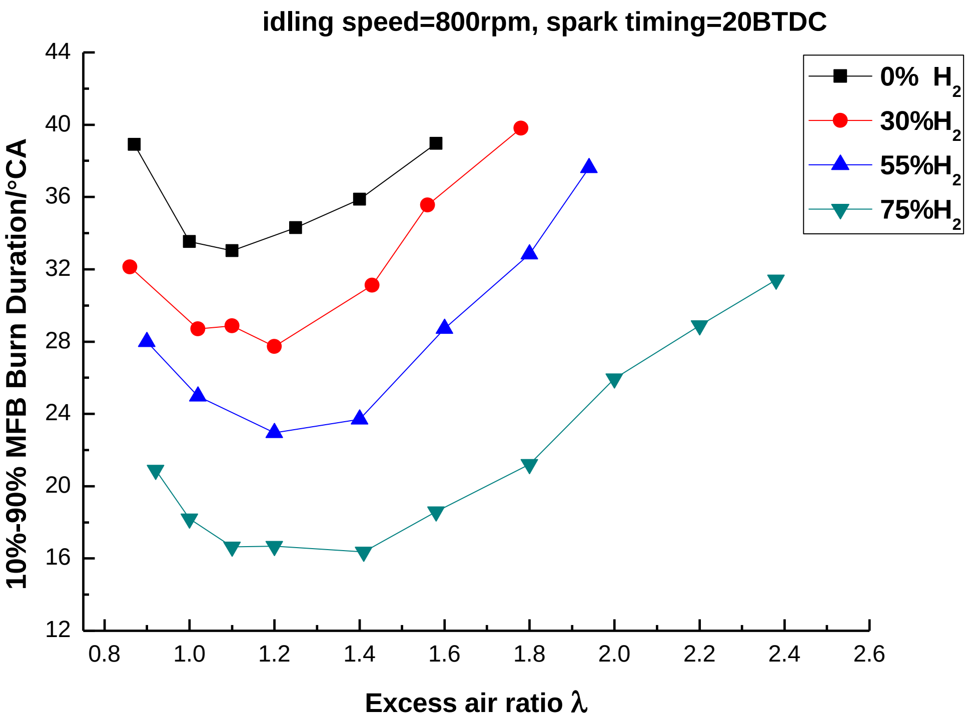


COV_{imep} versus excess air ratio

Idle Combustion and Emission Characteristics
idle speed=800rpm, spark timing=20BTDC

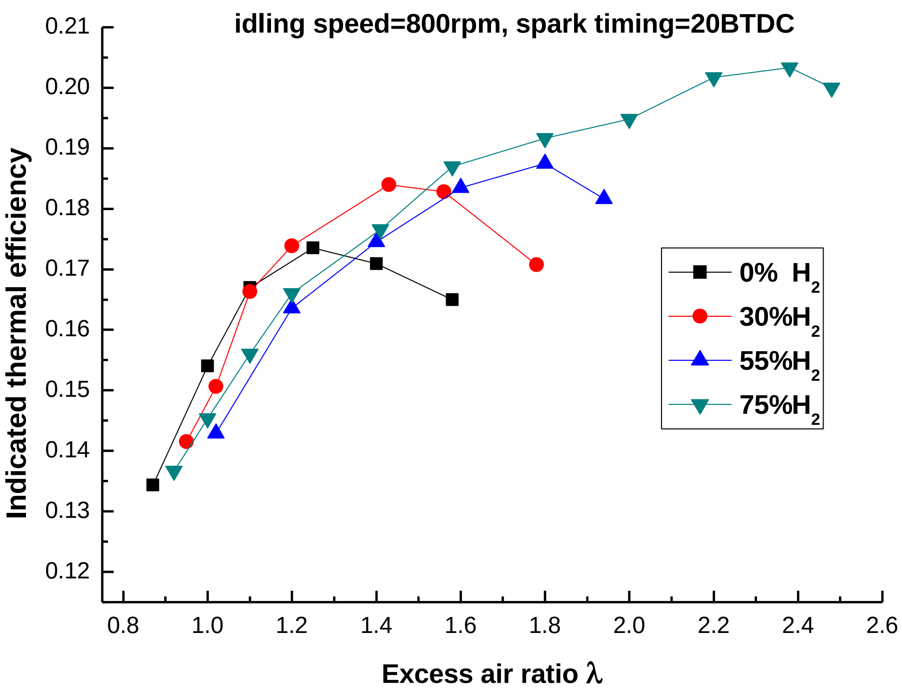


Spark to 10% MFB burn duration versus excess air ratio

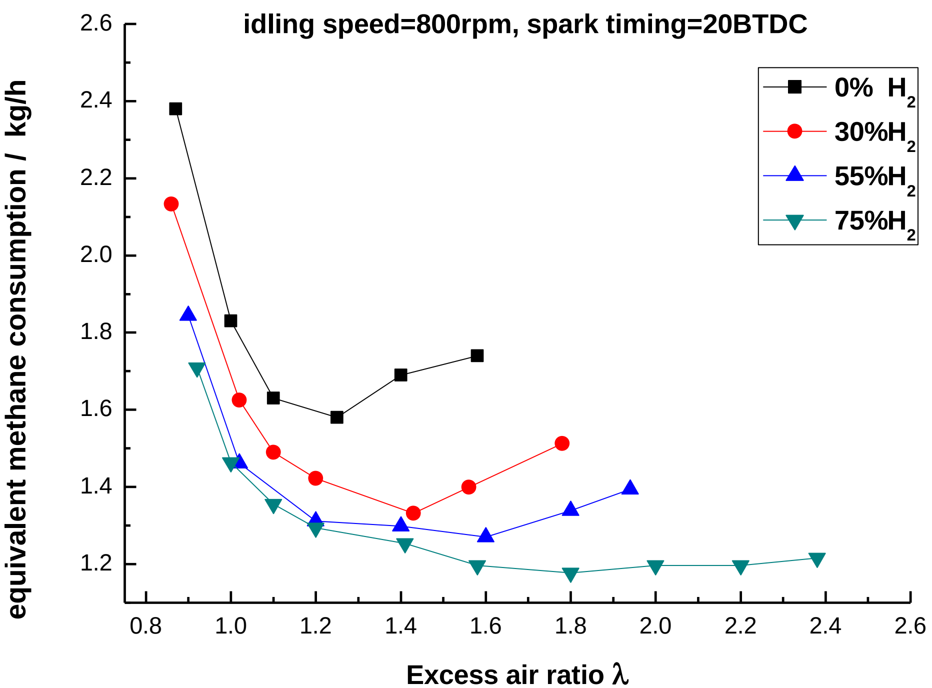


10% to 90% MFB burn duration versus excess air ratio

Idle Combustion and Emission Characteristics, idle speed=800rpm, spark timing=20BTDC

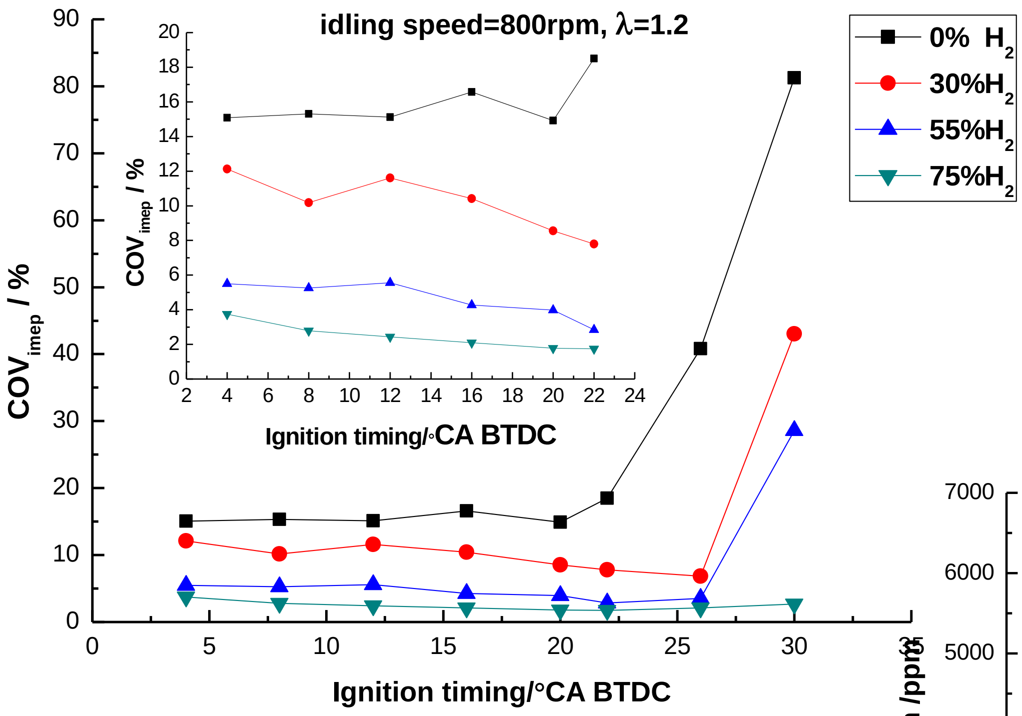


Indicated thermal efficiency versus excess air ratio

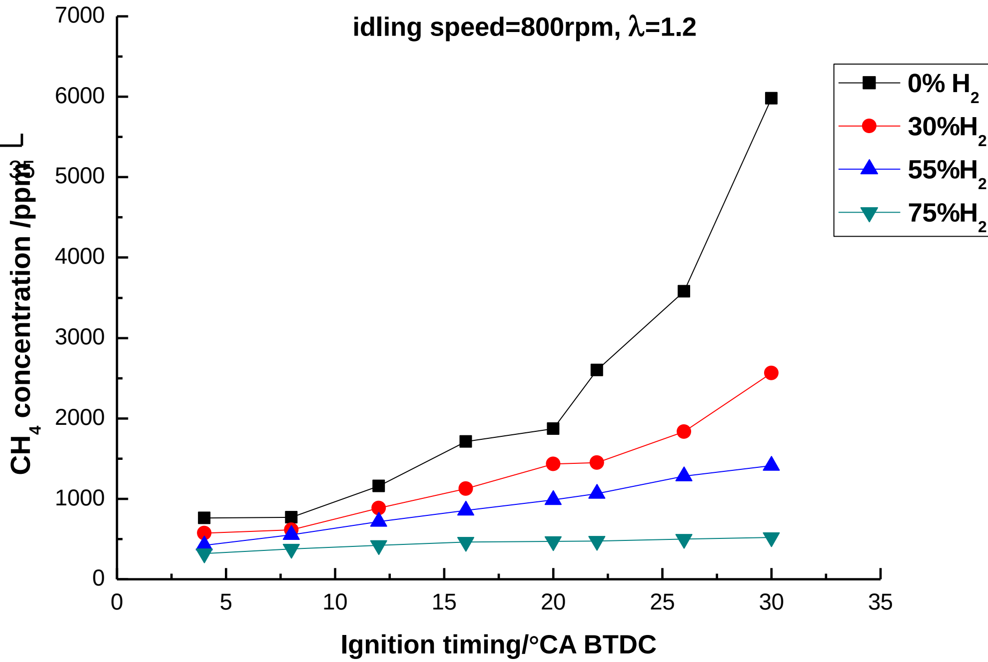


Equivalent methane consumption versus excess air ratio

Idle Combustion and Emission Characteristics, idling speed=800rpm, λ=1.2

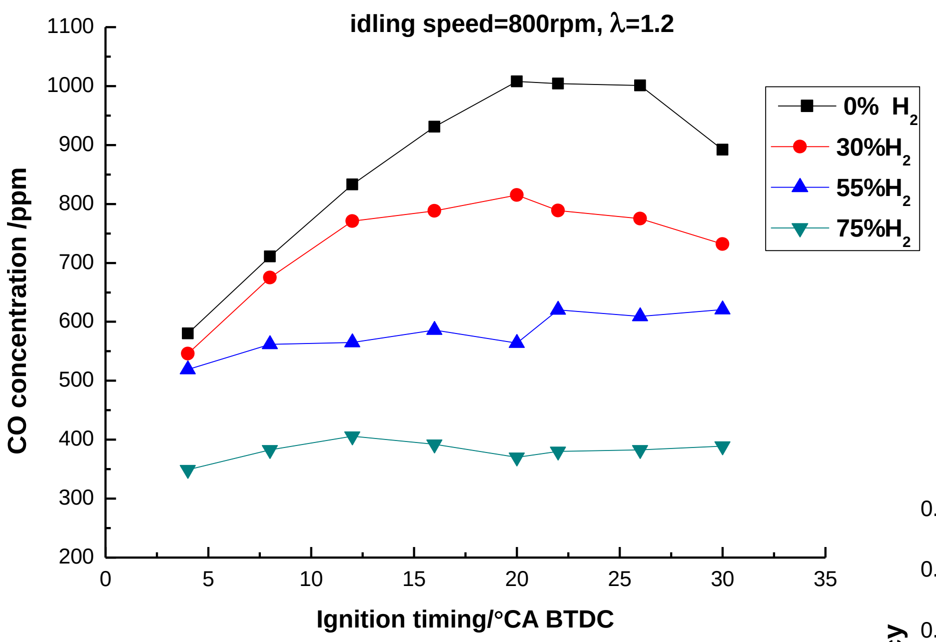


COV_{imep} versus ignition timings

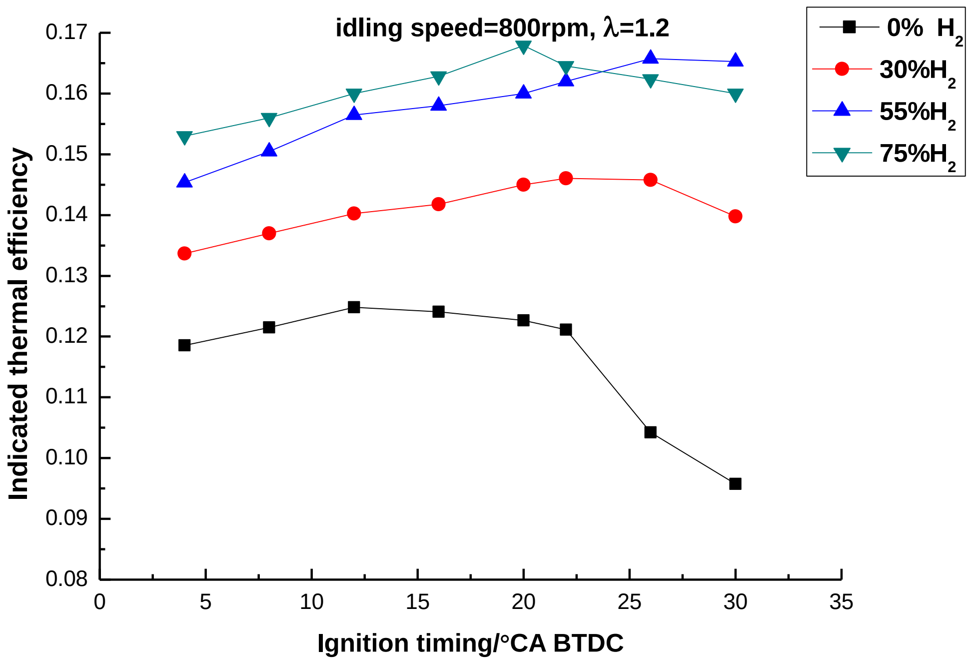


CH_4 emission versus ignition timings

Idle Combustion and Emission Characteristics, idling speed=800rpm, λ=1.2

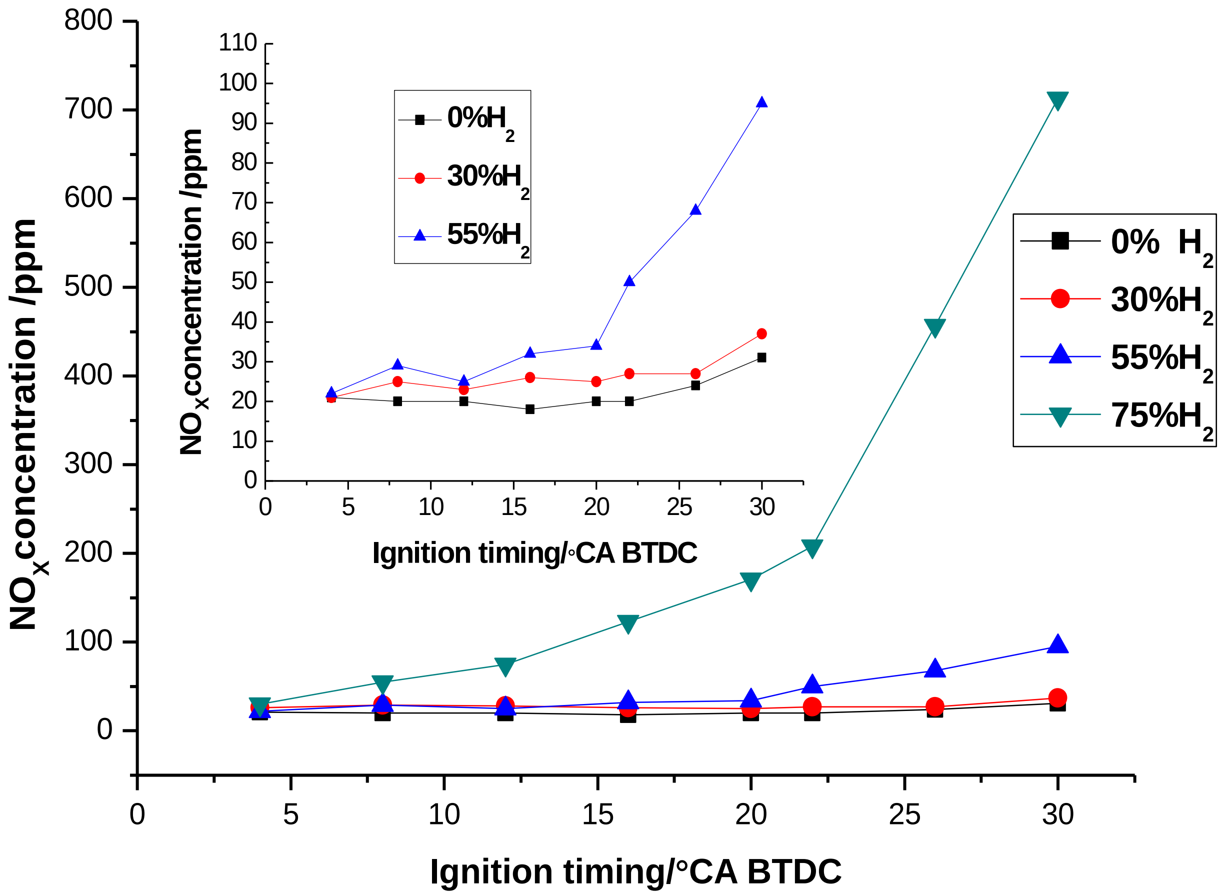


CO emission versus ignition timings



Indicated thermal efficiency versus ignition timings

Idle Combustion and Emission Characteristics, idling speed=800rpm, λ=1.2

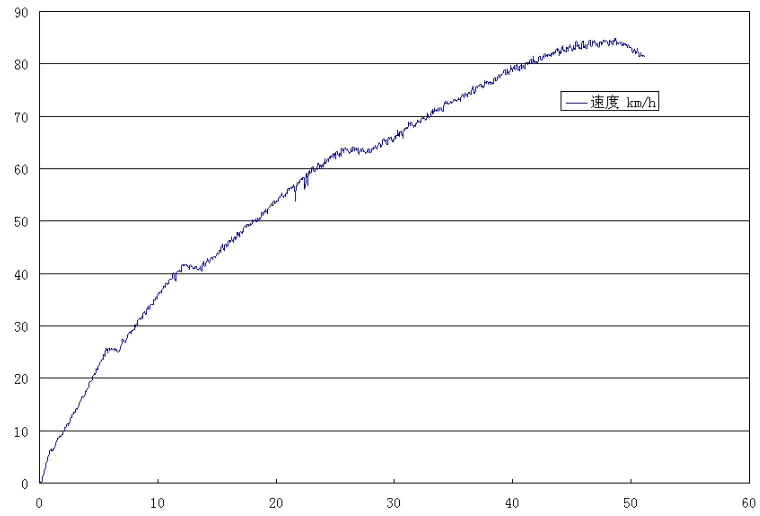


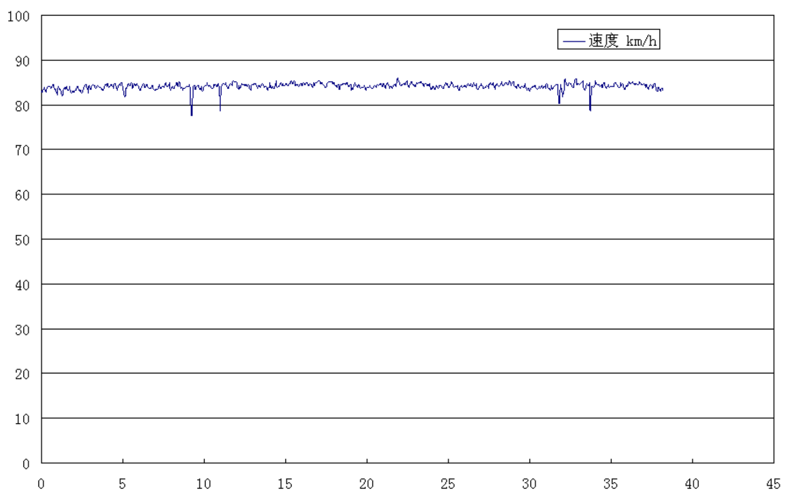
NO_x emission versus ignition timings

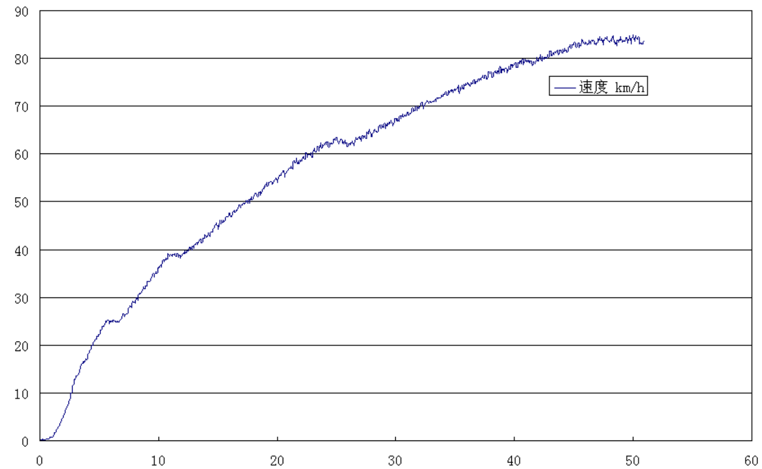
HCNG Bus Performance


清华新能源汽车工程中心
HCNG

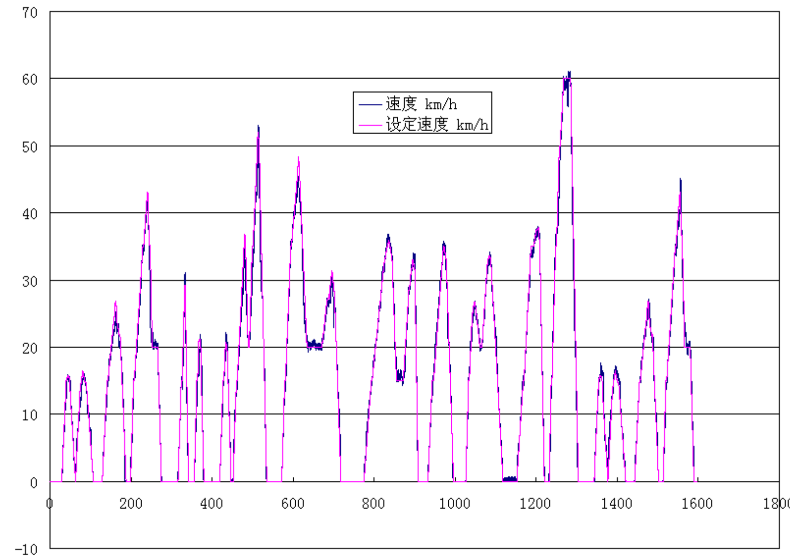
HCNG客车最高车速及加速试验

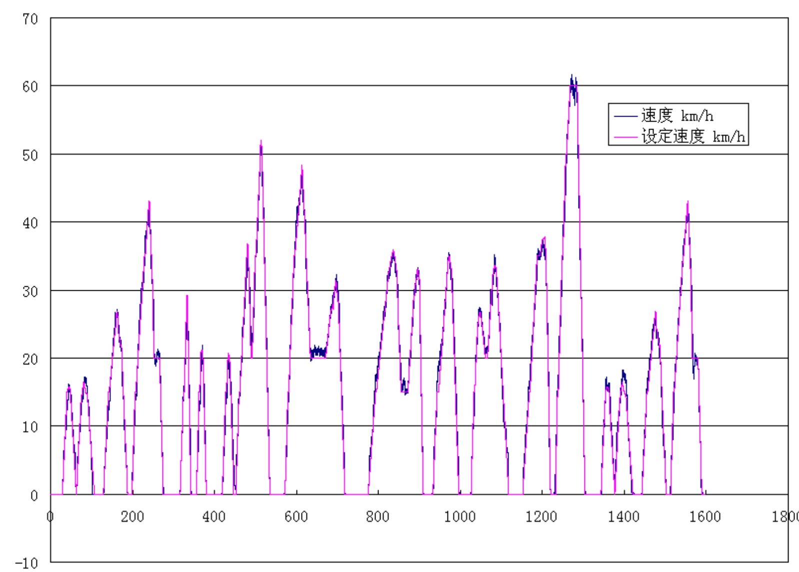






HCNG客车经济性试验





HCNG bus performance compared with CNG Bus

	Power Performance		Fuel Economy
	0~50km/h spped time (s)	Max Speed (km/h)	Equivalent CNG consumption (kg/100km)
CNG Bus	17.9	84.1	38.97
HCNG Bus	17.9	84.1	36.11

Some Projects

- MOST 863 Project "HCNG engine R & D"

- MOST 863 Project "HCNG Bus R/D and Hydrogen Generation by Renewable Energy", Cooperated with DOE.

- MOST 863 Project "Key Technologies Cooperation Research on Hydrogen Utilization based on Hydrogen Infrastructure"

Some Patents

- **“Calibration method of HCNG Engine”。 China patent：200710062635。**

- **“ HCNG fuel for optimized hydrogen fraction in HCNG engine”。China patent： 200710062636。**

- **“Control and operation methods for different hydrogen fraction in HCNG engine” China patents: 200710175797.9**

Some Papers

1	Combustion and emission characteristics of a port-injection HCNG engine under various ignition timings, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY, *JAN 2008, 33(2):816-822*
2	Effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engines, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY, *JAN 2008, 33(2):823-831*
3	Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY, *DEC 2007, 32(18):5067-5075*
4	Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY, *FEB 2008, 33(4):1416-1424*
5	Influence of different volume percent hydrogen/natural gas mixtures on idle performance of a CNG engine, ENERGY & FUELS, *MAY-JUN 2008, 22(3):1880-1887*

6	**Development and validation of a quasi-dimensional combustion model for SI engine fuelled by HCNG with variable hydrogen fractions, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY,** ***SEP 2008, 33(18):4863-4875***
7	**Effects of combustion phasing, combustion duration, and their cyclic variations on Spark-Ignition (SI) engine efficiency, ENERGY & FUELS,** ***AUG 2008, 22:3022-3028***
8	**Study on combustion behaviors and cycle-by-cycle variations in a turbocharged lean burn natural gas S.I. engine with hydrogen enrichment, INTERNATIONAL JOURNAL OF HYDROGEN**
9	**An investigation of optimum control of a spark ignition engine fueled by NG and hydrogen mixtures, INTERNATIONAL JOURNAL OF HYDROGEN ENERGY**
10	**A Quasi-Dimensional Combustion Model for SI Engines Fuelled by Hydrogen Enriched Compressed Natural Gas，SAE Paper No. 2008-01-1633, 2008**
11	**Development and Validation of an On-line Hydrogen-Natural Gas Mixing System for Internal Combustion Engine Testing, SAE Paper No. 2008-01-1580, 2008**

15	天然气火花点火发动机循环变动的分析方法，内燃机工程，2008年第29卷第3期：41-46
16	氢内燃机缸内燃烧特性，内燃机工程，2008年第29卷第1期：29-33
17	火花点火天然气掺氢发动机稀燃极限的影响因素，农业机械学报，2008年第39卷第7期：9-13
18	不同掺氢比天然气发动机的燃烧排放特性，农业机械学报，2008年第39卷第8期：1-4
19	CA488活塞的强度分析及结构改进，机械强度，2007年第29卷第3期，501-506
20	增压稀燃天然气掺氢发动机排放特性，内燃机工程（已接收，待发表）
21	A Quasi-Dimensional Combustion Model for SI Engines Fuelled by Hydrogen Enriched Compressed Natural Gas，SAE Paper No. 2008-01-1633, 2008
22	Development and Validation of an On-line Hydrogen-Natural Gas Mixing System for Internal Combustion Engine Testing, SAE Paper No. 2008-01-1580, 2008
23	天然气发动机燃烧方式分析，车用发动机，2007年第5期，18-21

Conclusions

- Lean burn is one of the effective approach for HCNG Engine, and Spark timing optimization is necessary.
- 15~25% Hydrogen fraction in volume of HCNG is a good range for the HCNG Engine. Primary Research results indicate that 55% Hydrogen fraction in volume of HCNG is also another choice for the HCNG Engine.
- Fueled by 20% HCNG the engine's emission can meet Euro EEV (Enhanced Environmental Vehicle) power output, fuel consumption can be kept almost unchanged compared with CNG engine.

Proposals

- HCNG ENGINE IS ONE OF THE BEST TECH. APPPROACH IN AUTO TO MEET MORE STRICT EMMISSION AND ENERGY REQUIREMNENTS.

- Suggest china national and domestic government fund CNG/HCNG auto projects (especially buses) scale and level.

- Suggest as soon as possible start china national and domestic HCNG（including producer gases） demo projects in order to save energy and protect environment.


Thanks for
Attention !