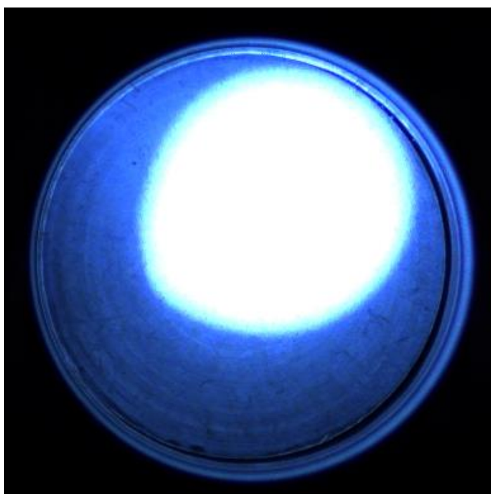
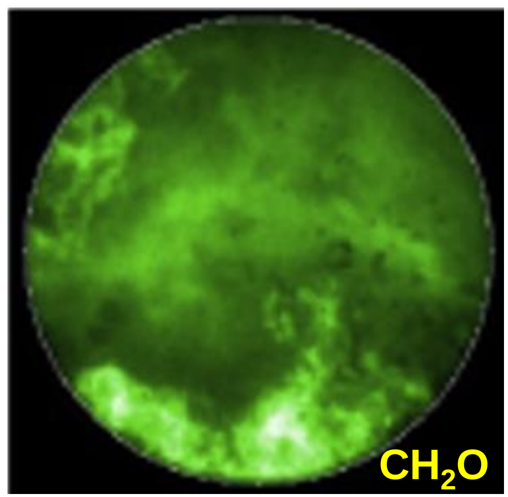
内燃机中的爆震燃烧

汇报人：王志
清华大学，汽车安全与节能国家重点实验室



HCCI knock



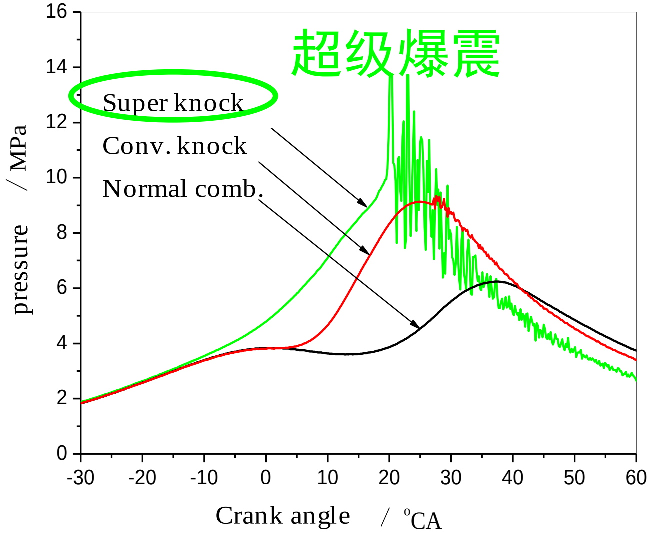
SI knock

Deto-knock

第一届全国青年燃烧学术会议
2015 年9 月18 - 20日，上海

高功率密度汽油机强化燃烧的负荷极限？

Power and fuel consumption



Wang Z, IJER, 2015

Spark electrode broken

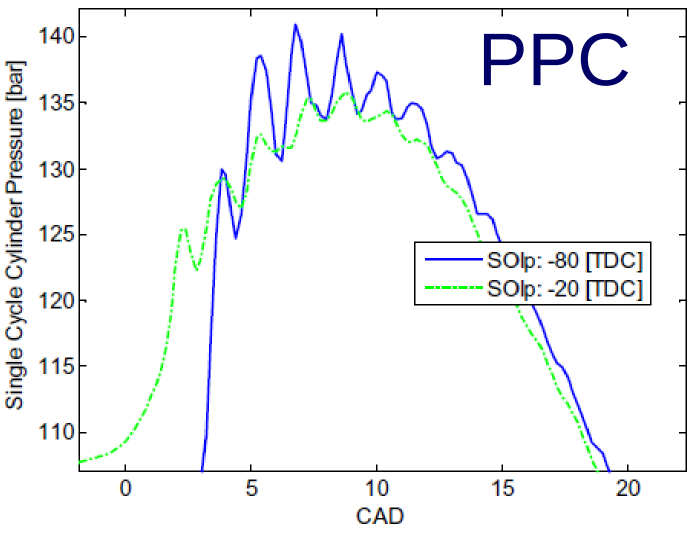
Exhaust valve melt

Piston ring land crack

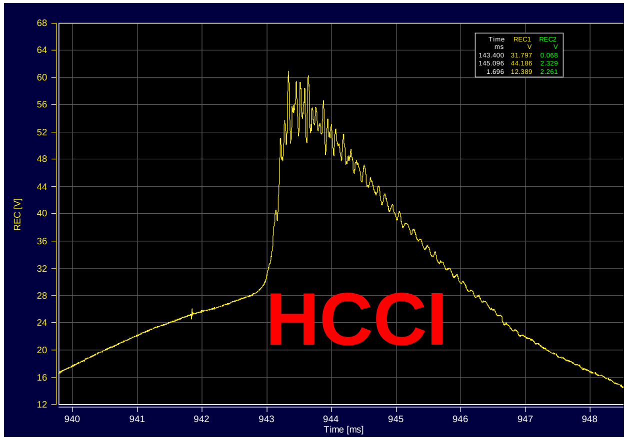
- 内燃机中，直喷增压小排量是汽油机节油的有效途径。但随增压提高（20-30）
- 出现了新的敲缸模式，极具破坏性，瞬时缸内压力甚至超过400bar，常规手段无法消除。VW（2005）称为Unwanted Pre-ignition，AVL（2009）称为Mega Knock， Shell （2009）年称之为Super-knock，SWRI （2011）称为LSPI，我们（2006）国家863项目中称之为超级爆震。
- 目前国际各大汽车公司都出现了超爆，各大机构正在研究其机理和解决方案。
- SK different from conv. knock (end-gas auto-ignition, pioneers in this field of science: Sokolik and Voinov [1], Miller [2] Male [3]) , SK may relate to detonation.

内燃机爆震燃烧的普遍性

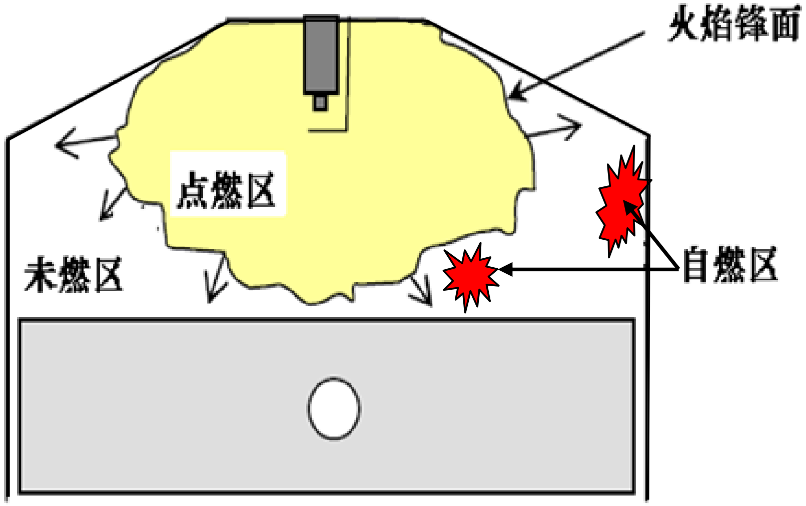
- 除增压小排量汽油机外，内燃机中的先进燃烧模式:均质压燃（HCCI）、部分预混压燃（PPC,PPCI）、汽油压燃（GCI）和双燃料燃烧（DFC, RCCI等）能明显降低油耗和排放，但也都遇到了大负荷超级爆震或粗暴燃烧的问题！



SAE 2009-01-0944



内燃机爆震燃烧机理与控制



爆震现象
火焰传播速度与
混合气自燃速度的竞争

科学问题
湍流燃烧、压力波与
燃料化学反应动力学的交互？

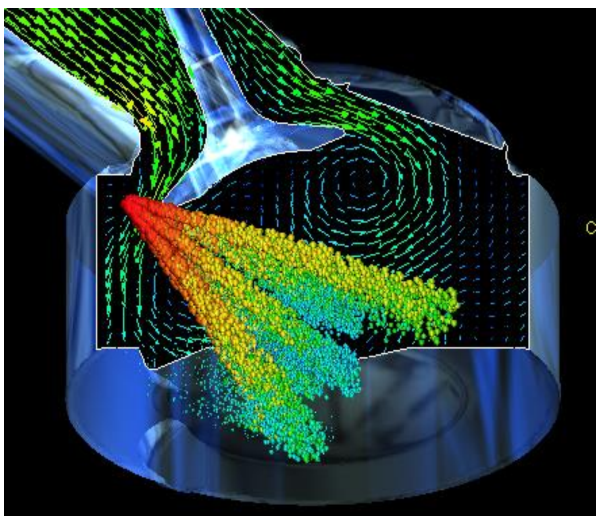
国际难题
内燃机爆震机理？
爆震的抑制及合理利用

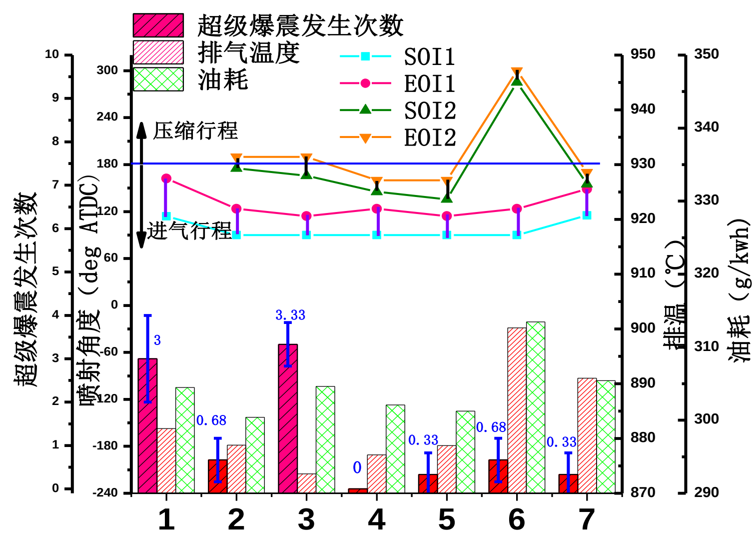
汇 报 提 纲

1. 内燃机爆震燃烧过去的工作
2. 前沿与难点问题及国际进展
3. 未来可能的研究方向与合作

1. 内燃机爆震燃烧过去的工作

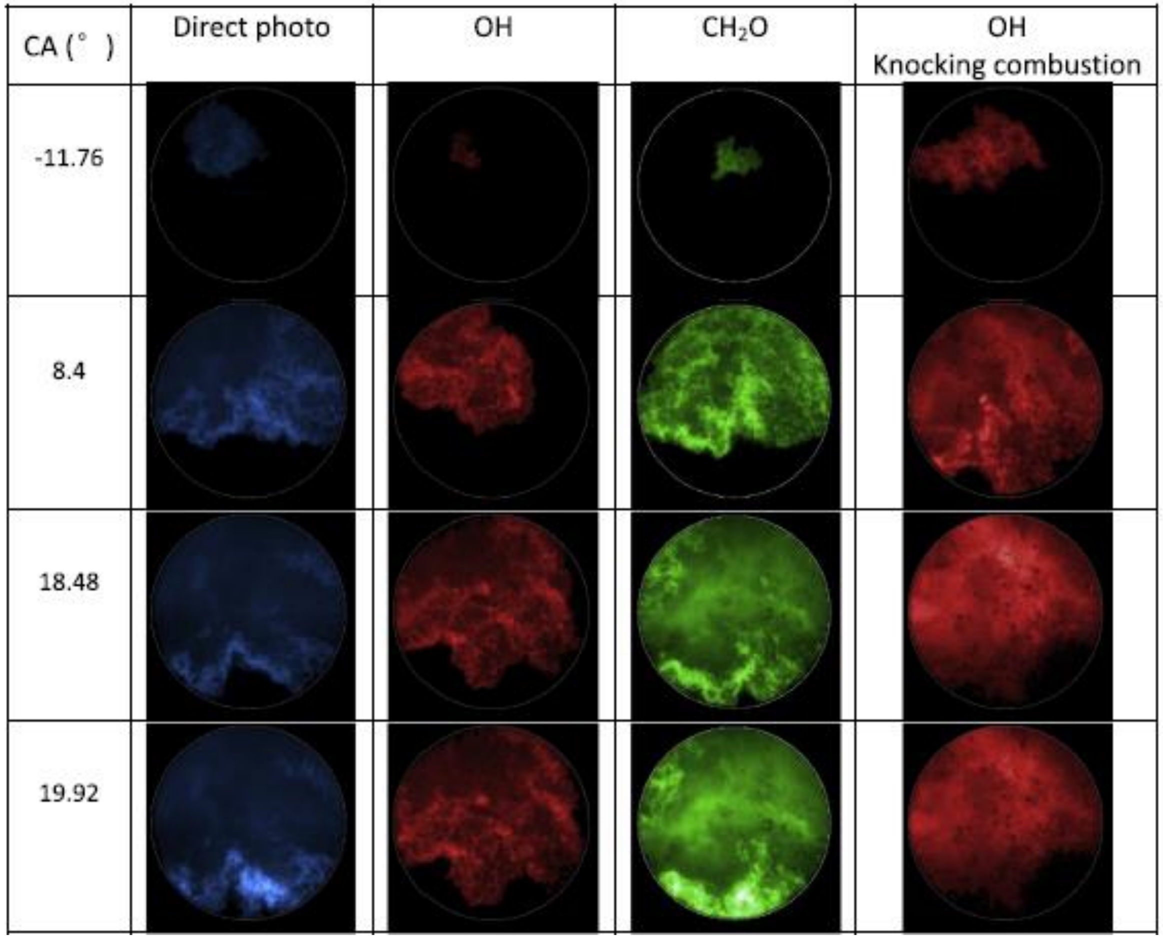
- 从常规爆震到超级爆震
- 超级爆震的机理
- 超级爆震的抑制*

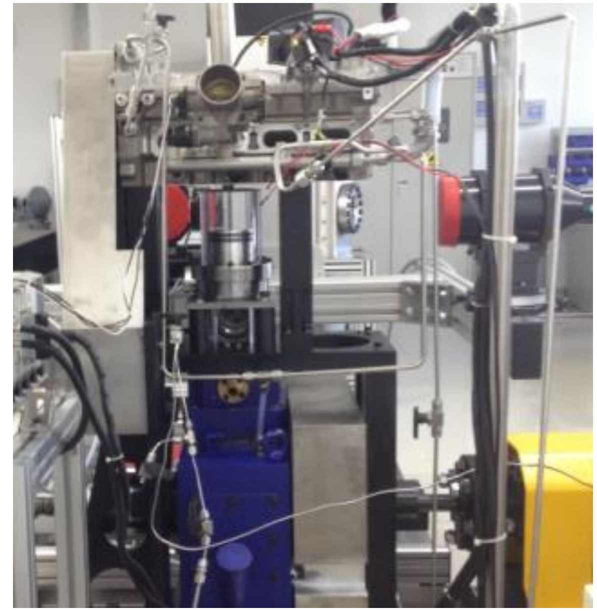


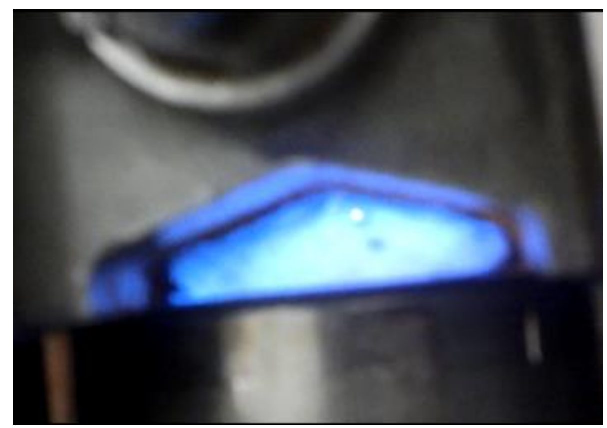


● 与国内主要汽车企业合作完成863项目，已在奇瑞、吉利、长城和东风新开发的GDI发动机上采用。

可视化发动机上SI爆震光学诊断





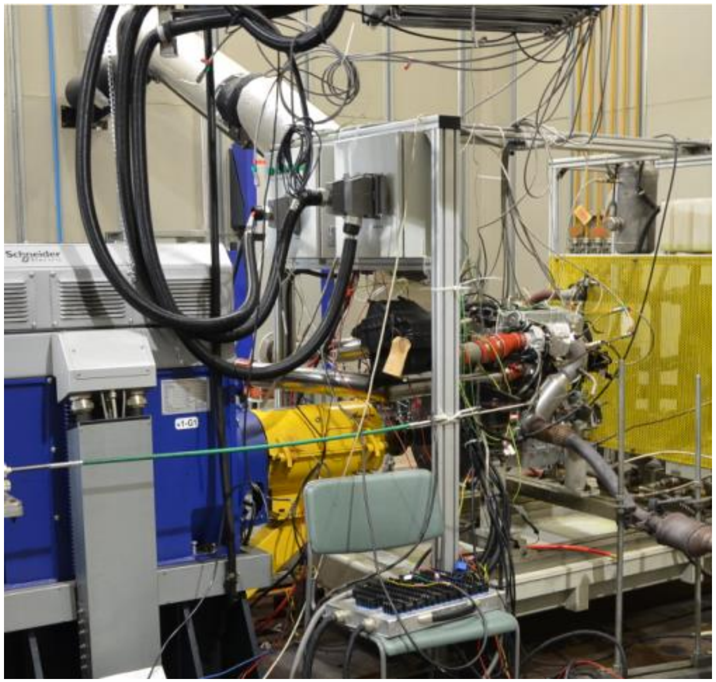


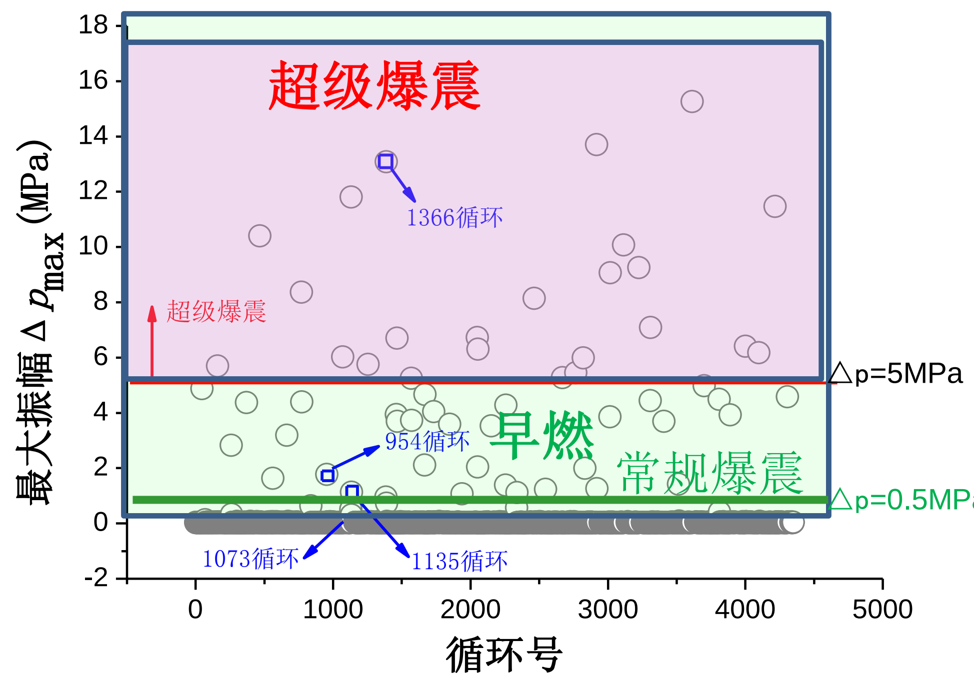
❑机理：末端混合气的顺序自燃

Xiao Ma, Zhi Wang*, et al. An optical study of in-cylinder CH2O and OH chemiluminescence in flame-induced reaction front propagation using high speed imaging. Fuel, 2014. 134: 603-610

内燃机爆震研究二——超级爆震

大量采集超级爆震循环试验样本，对含有超级爆震事件的前后50个循环进行燃烧特征参数提取：





- **早燃远远多于超级爆震发生次数。因为大多数早燃并不导致超级爆震（如1073#，954#）。也就是说，早燃不是超级爆震的充分条件；**
- **但超级爆震燃烧循环中总是有早燃发生。**

甄别早燃和超级爆震

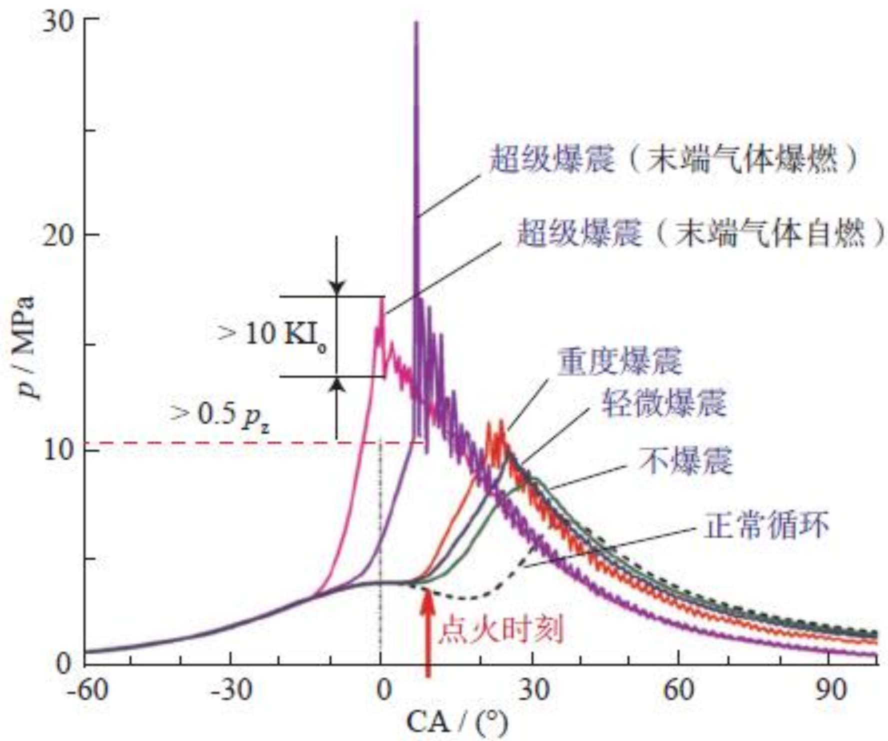


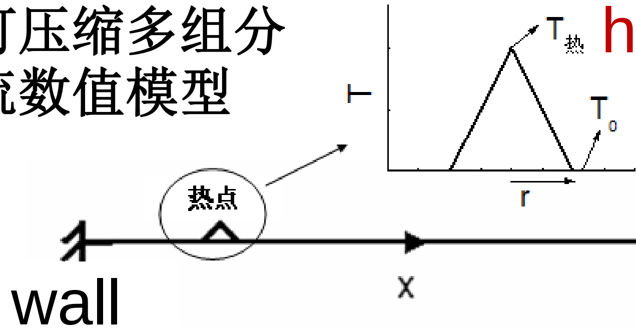
图 3　典型的早燃和正常燃烧的缸压曲线 [10]

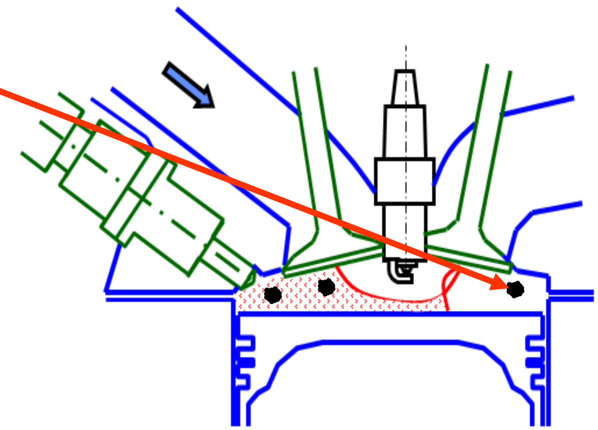
- 超级爆震一定发生了早燃，但早燃不一定发生超级爆震
- 早燃可以导致超级爆震、强烈爆震、轻微爆震和不爆震

Zhi Wang, Hui Liu, Tao Song, Yunliang Qi, Xin He, Shijin Shuai and JianXinWang . Relationship between super-knock and pre-ignition. **International Journal of Engine Research**. 2014

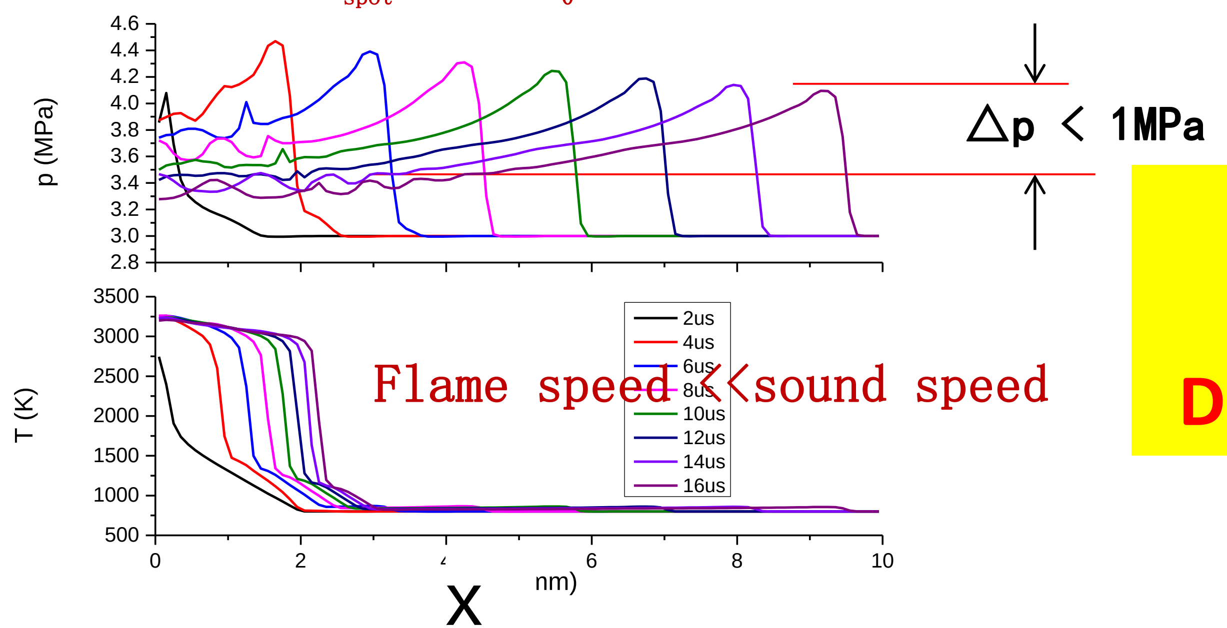
一维CFD解析：热点诱导的爆燃

一维可压缩多组分
反应流数值模型





（T_{spot}=1800K，T_0=800K）

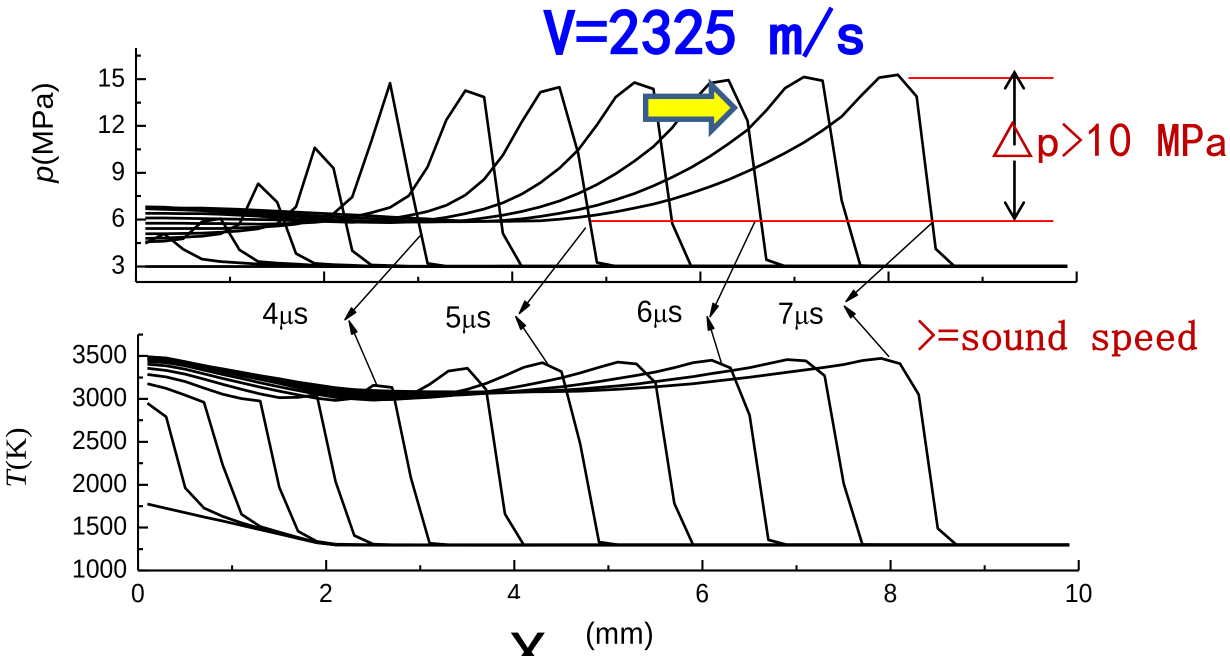


Hotspot
induced
Deflagration

Zhi Wang, Hui Liu, Tao Song, Yunliang Qi, Xin He, Shijin Shuai and JianXinWang . Relationship between super-knock and pre-ignition. **International Journal of Engine Research. 2014**

一维CFD解析：热点诱导的爆轰

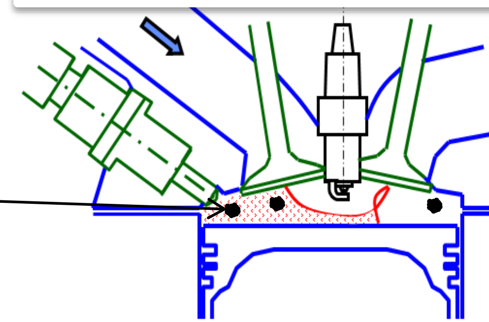
Pressure wave coupled with chemical kinetics



（$T_{hotspot}$=1800K，T_0=1300K）

Hotspot induced Detonation

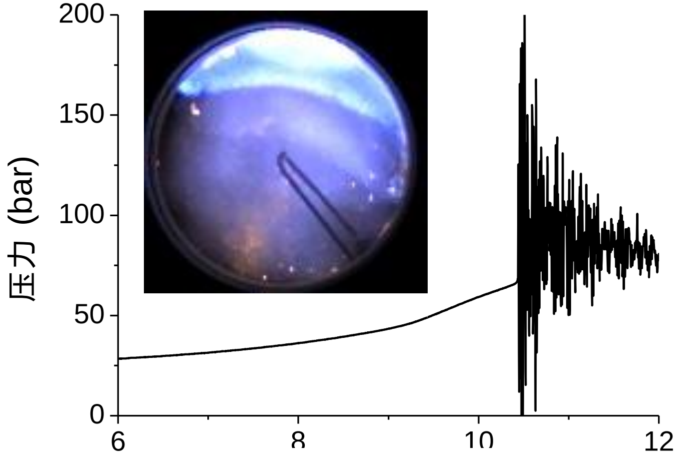
10mm长度范围0.1CA时间即可诱导出10MPa 汽油机燃烧室中正好具备这种条件



- 温度曲线与压力曲线呈现了明显的同步传递的效应。
- 压力波传递到某处，该处的混合气随即发生自燃着火，燃烧产生的能量反过来传递给压力波使得压力波峰值持续增加。

Zhi Wang, Hui Liu, Tao Song, Yunliang Qi, Xin He, Shijin Shuai and JianXinWang . Relationship between super-knock and pre-ignition. **International Journal of Engine Research. 2014**

爆震研究三——用RCM研究超级爆震机理



起爆过程

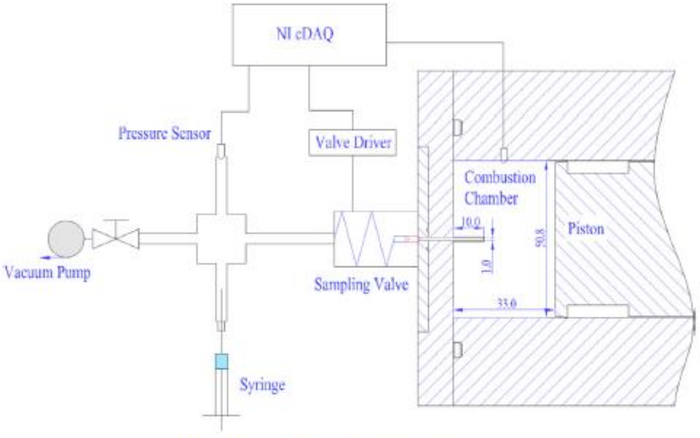
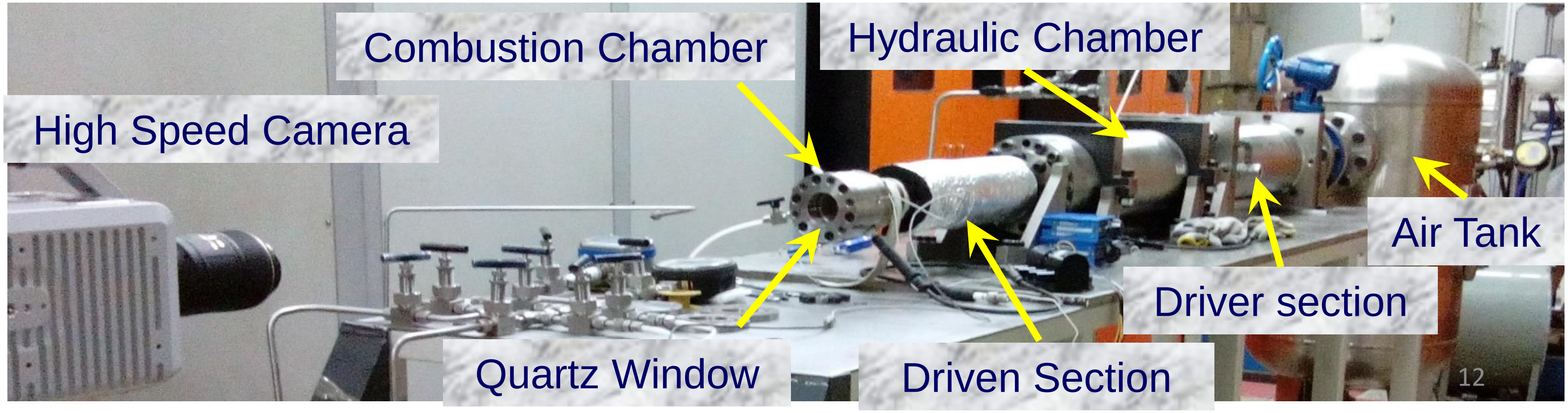


Fig. 1. The schematic of the fast sampling system.

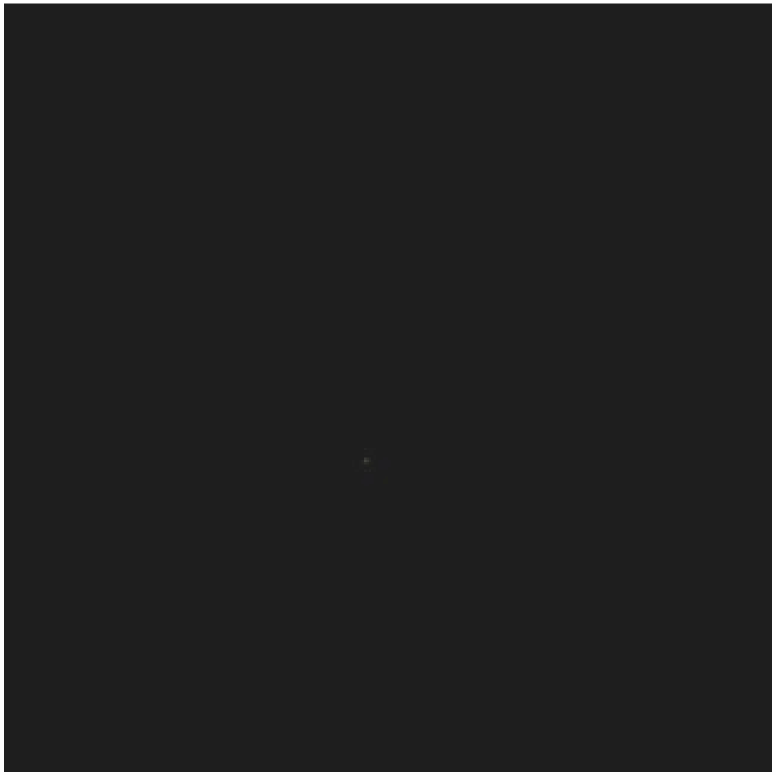
快速采样

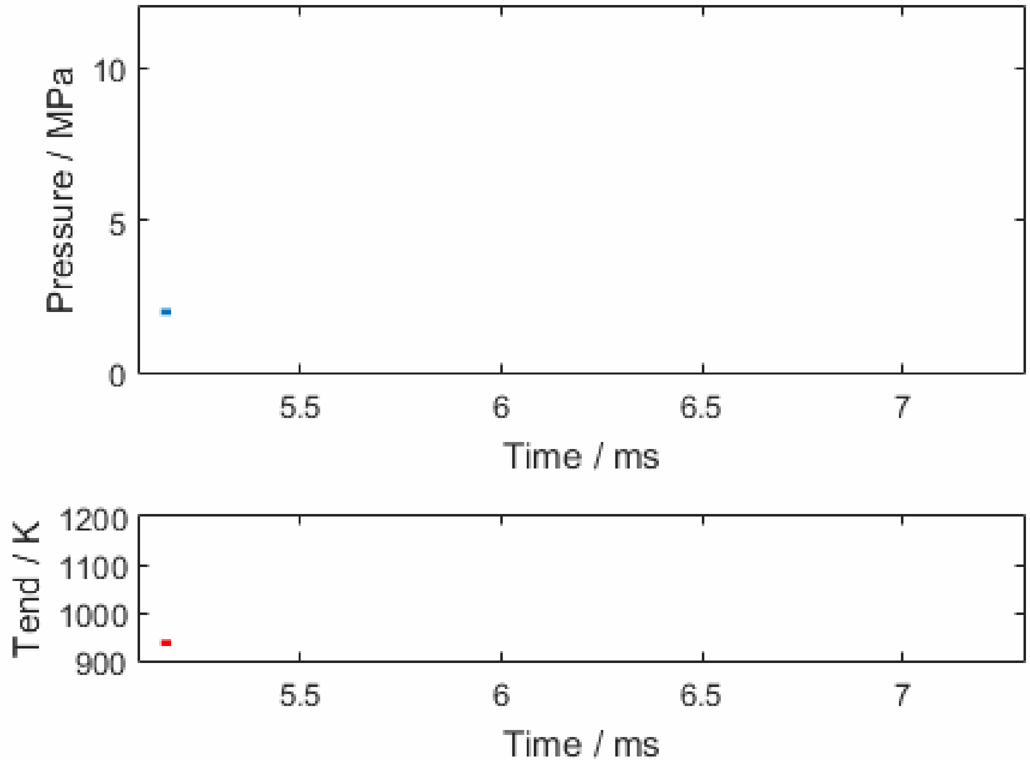
He&Wang. Intermediate species measurement during iso-butanol auto-ignition. Combustion and Flame.162(2015)3541–3553



“第一次拍摄到了随机早燃诱发的超级爆震”

Random pre-ignition and super-knock in high-T,P stoichiometric mixture

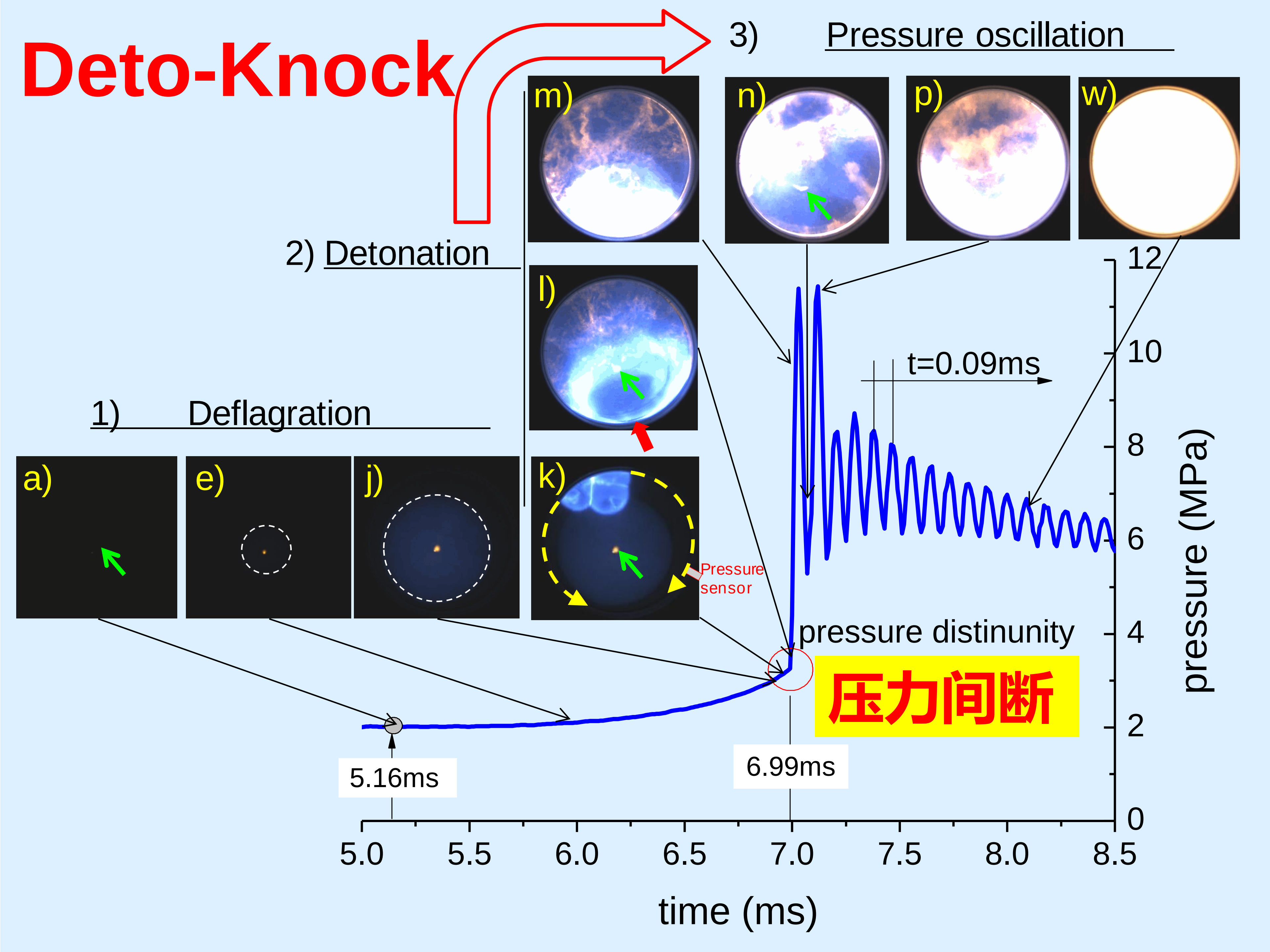




This is the Deto-knock!

Hotspots induced Deflagration to Detonation to Pressure oscillation (DDP)

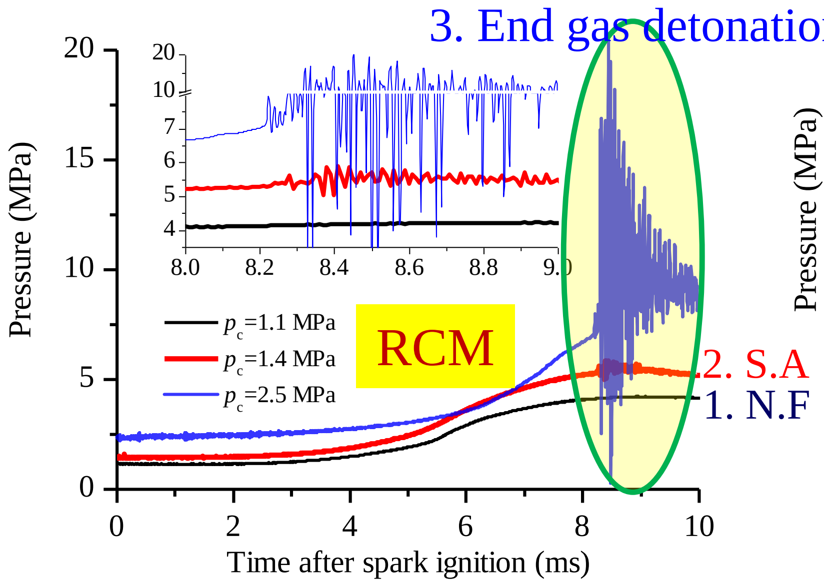
Wang, Qi, He et al. Hotspot-induced deflagration to detonation. Fuel .144 (2015)
Di, He, Zhang, Wang, et al, Low Temperature Ignition of Iso-octane, Combust. Flame 161, (2014).

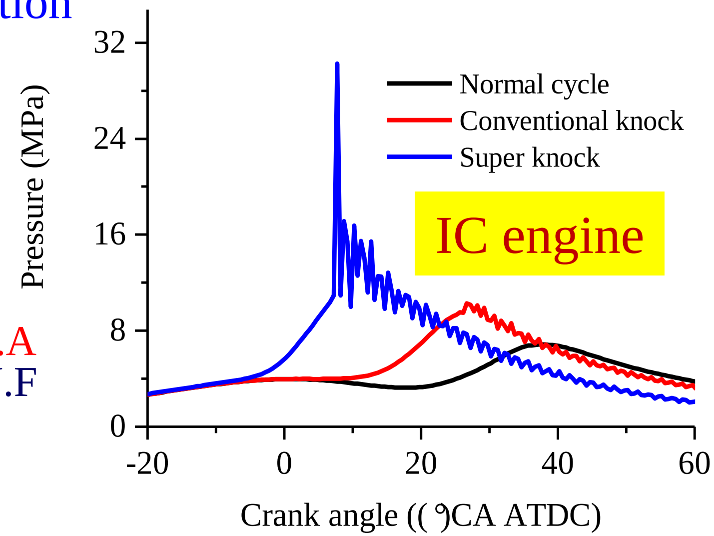

Deto-Knock
3) Pressure oscillation
m)
n)
p)
w)
2) Detonation
l)
1) Deflagration
a)
e)
j)
k)
Pressure sensor
t=0.09ms
pressure distinunity
压力间断
5.16ms
6.99ms
pressure (MPa)
time (ms)
0
2
4
6
8
10
12
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5

发现了末端混合气中的三种典型燃烧模式

Detonation (RCM) and Super-knock (Engine)

比较了快压机和发动机中的三种燃烧模式：火焰传播、顺序自燃、爆轰



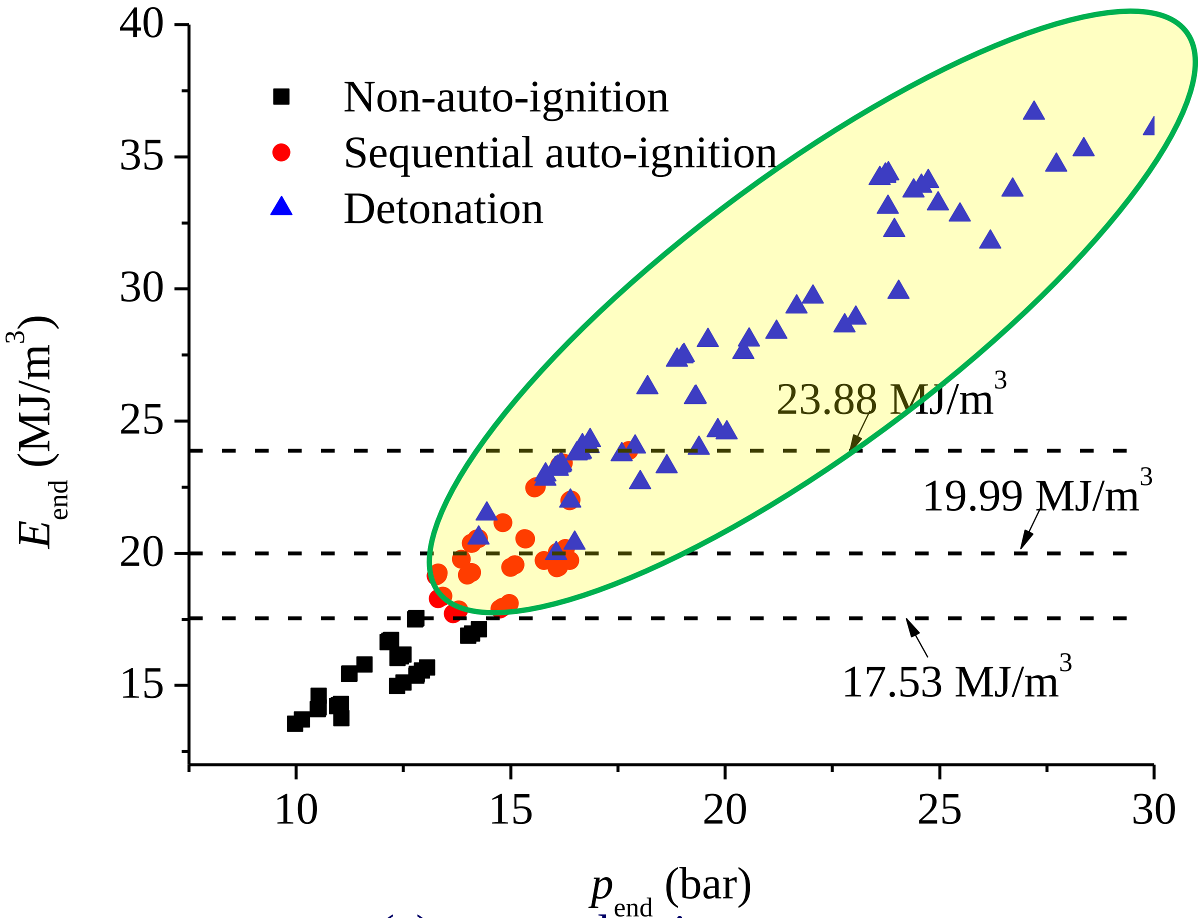


Effects of thermodynamic conditions on the end gas combustion mode associated with engine knock. **Combustion and Flame**. 2015.

Conditions		Amplitude (Mpa)		T_{ai}(K)		p_{ai}(Mpa)	
RCM	Engine	RCM	Engine	RCM	Engine	RCM	Engine
p_{TDC}=1.1 MPa	Normal	-	-	-	-	-	-
p_{TDC}=1.4 MPa	Knock	0.36	0.45	863.2	802.0	5.29	9.53
p_{TDC}=2.5 MPa	Super knock	8.30	8.87	820.8	826.4	7.34	10.94

- Pressure oscillation and knock onset conditions of detonation case (3rd mode) in RCM are close to super-knock in IC engine.
- To reveal 3rd mode of end gas detonation, detonation initiation is the key!

宽温度压力条件下的自燃模式

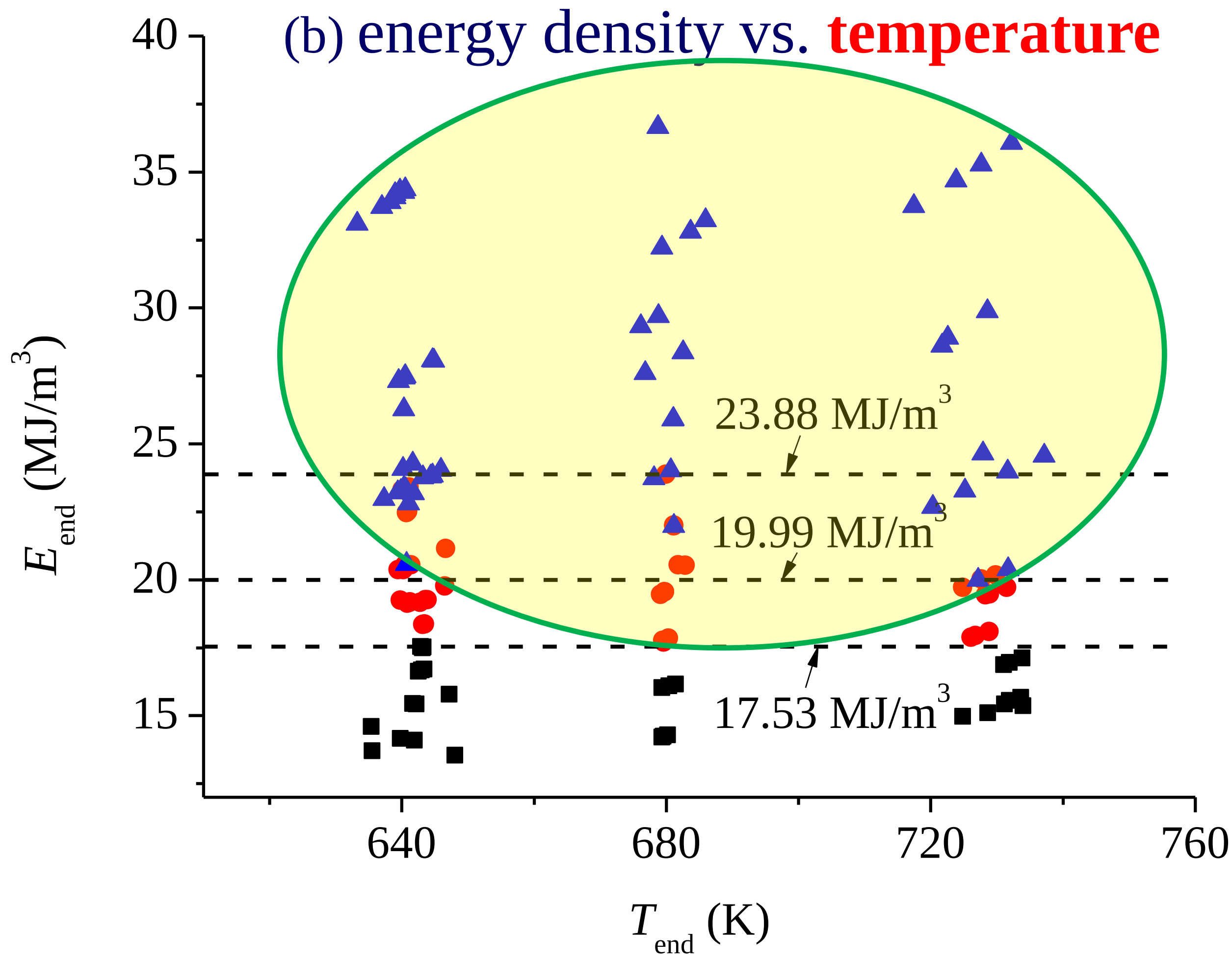


(a) energy density vs. pressure

- Effects of thermodynamic conditions on the end gas combustion mode associated with engine knock. **Combustion and Flame**. 2015.

- End gas combustion mode is closely related to the mixture energy density.
- Detonation is more likely to occur at higher mixture energy density.

宽温度压力条件下的自燃模式



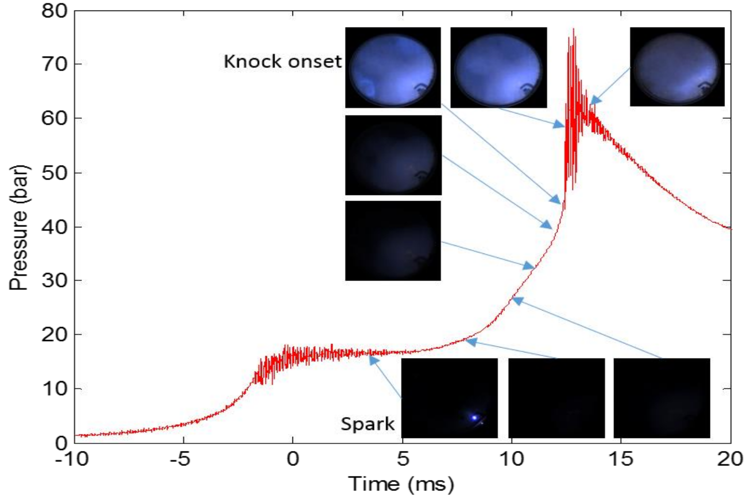
- Effects of thermodynamic conditions on the end gas combustion mode associated with engine knock. **Combustion and Flame**. 2015.

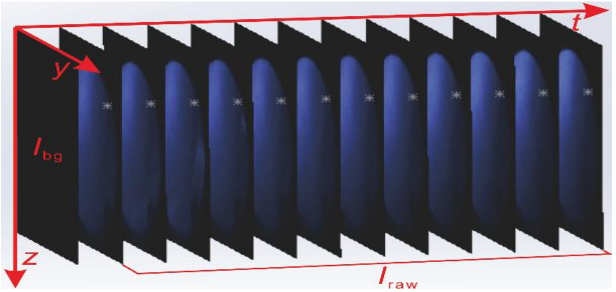
末端混合气自燃模式取决于能量密度！而不是温度。

- End gas combustion mode is closely related to the mixture energy density.
- Detonation is more likely to occur at higher mixture energy density instead of temperature.

用化学发光法扑捉激波

为了进一步弄清起爆前过程：开发了CH*化学发光直接扑捉爆轰前激波的方法





Remove the background noise

Single pixel luminosity time-history

High-pass filtering

FFT for luminosity Spectrum

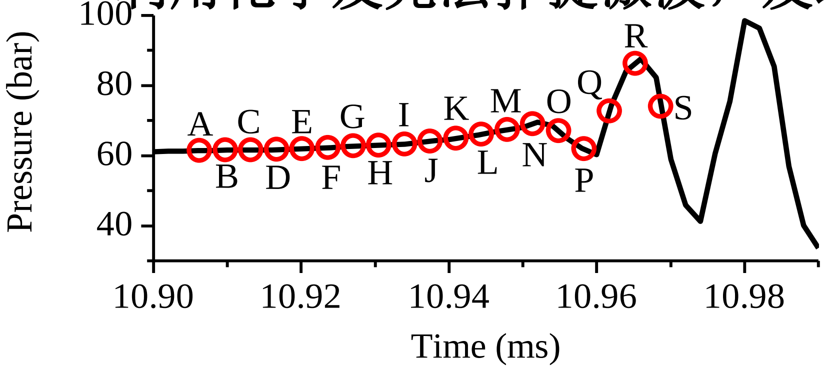
A novel experimental method was developed to directly visualize the shock wave by the presence of CH* radicals （431.5nm）.

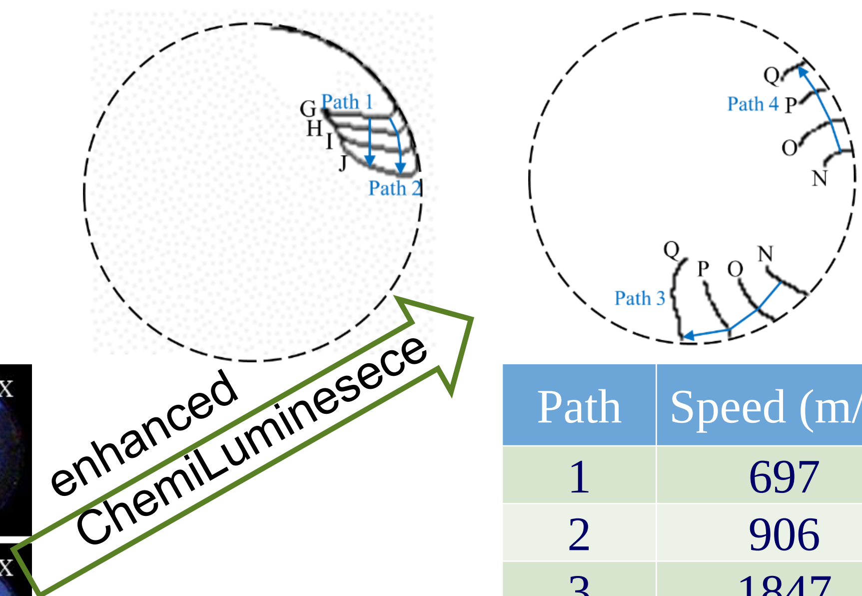
X. He, Y. Qi, Z. Wang*, et al, “Visualization of the mode shapes of pressure oscillation in a cylindrical cavity”, Combustion Science and Technology, 2015.

发现了激波反射交汇起爆现象

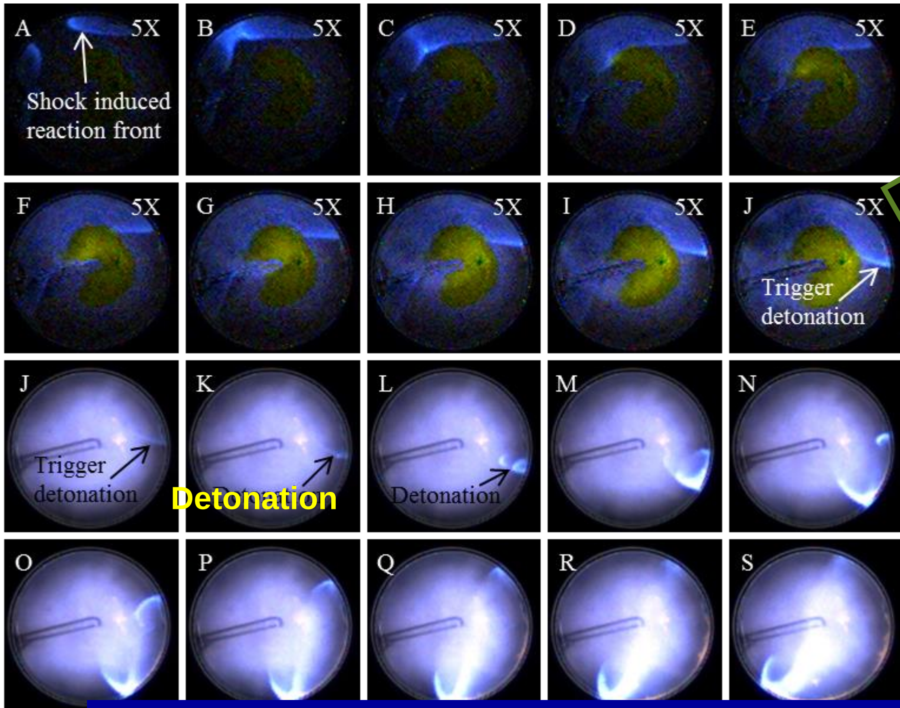
Shock Wave Reflection Inducing Detonation (SWRID)

利用化学发光法扑捉激波，发现了激波反射诱导的爆轰（SWRID）





Path	Speed (m/s)
1	697
2	906
3	1847
4	1533



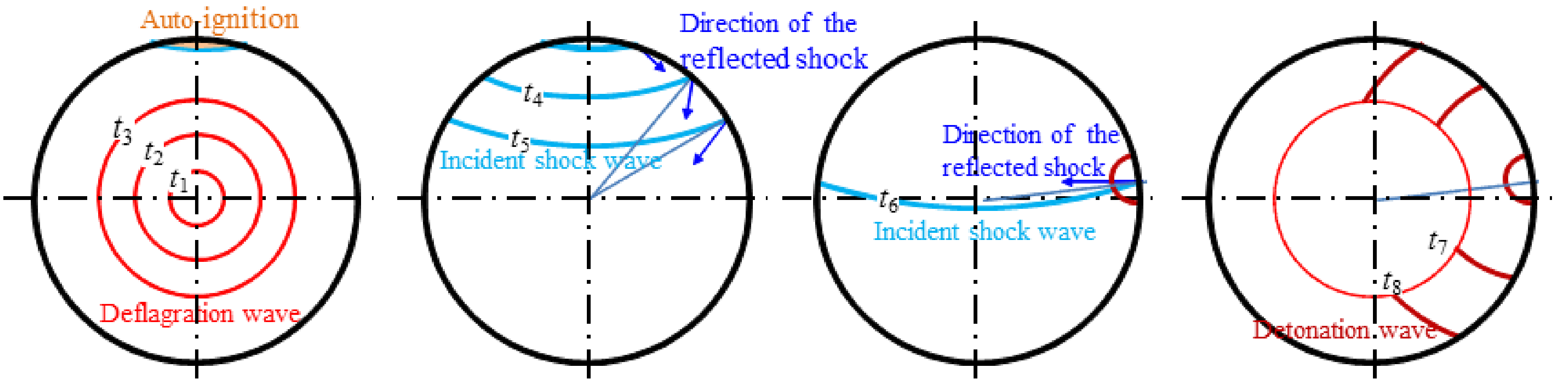
D_{CJ} (m/s)	p_{di} (Mpa)	T_{di} (K)
1840	6.3	824

- Detonation is initiated by shock wave reflection at the time of Image J

Wang Z, He X, Liu H, et al. 25th ICDERS, Leeds, UK, 2015.

揭示激波反射诱导爆轰的机理

Mechanism of SWRID revealed



a) Flame propagation b) Shock propagation c) Deto. initiation d) Deto. propagation

The detonation is typically initiated near the cylinder wall and about 90 degree (t_6) to the first auto-ignition location (t_3)

Wang Z, He X, Liu H, et al. Initiation of detonation in iso-octane/air mixture: 25th International Colloquium on the Dynamics of Explosions and Reactive Systems, Leeds, UK, 2015.

传统爆震连续运行会烧顶，超级爆震为什么常断环？

压力震荡破坏边界层，大幅增强传热

Conventional knock

热破坏

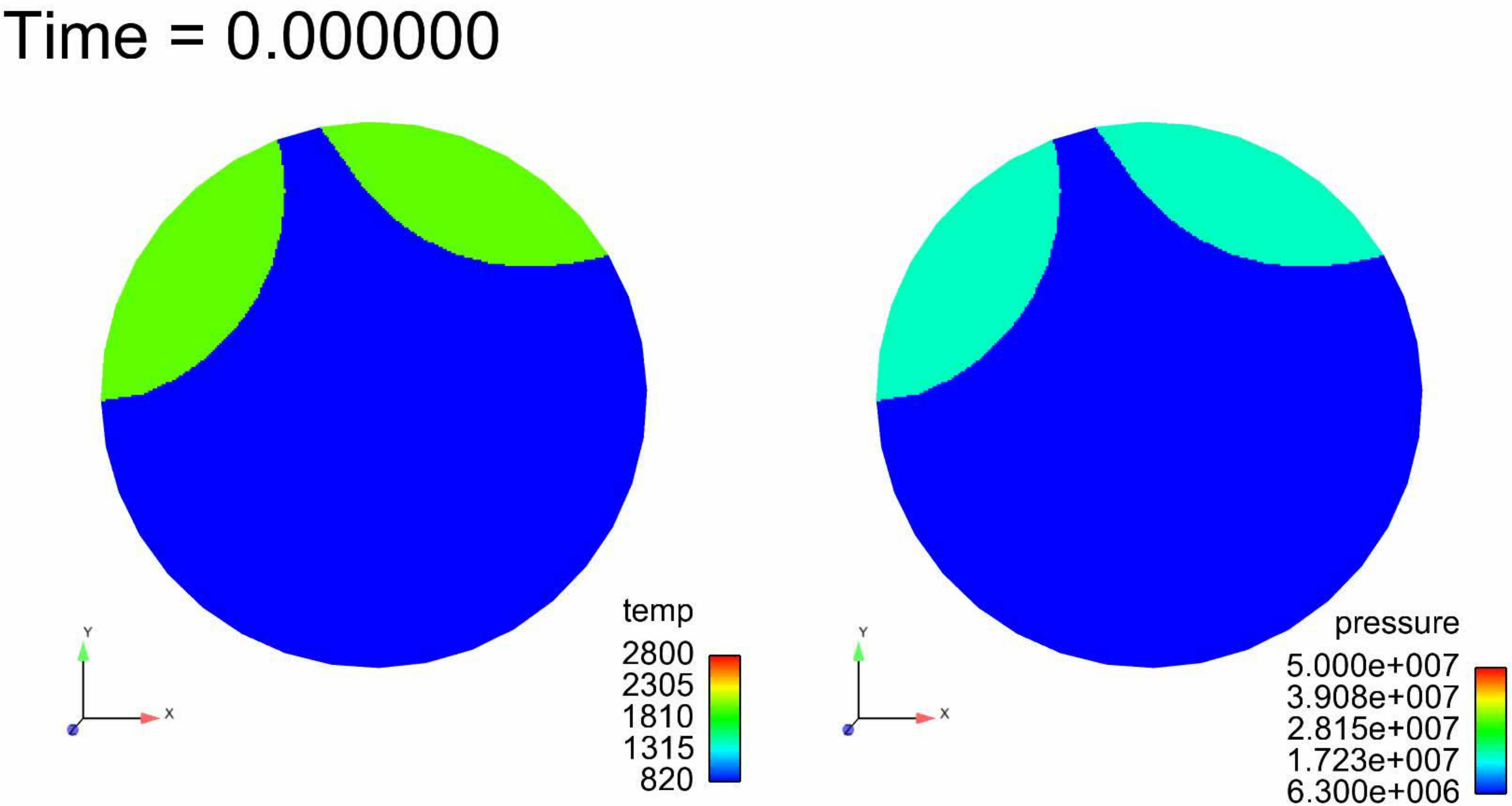
(NWDI: Near Wall Detonation Initiation，近壁起爆）

Deto-knock!

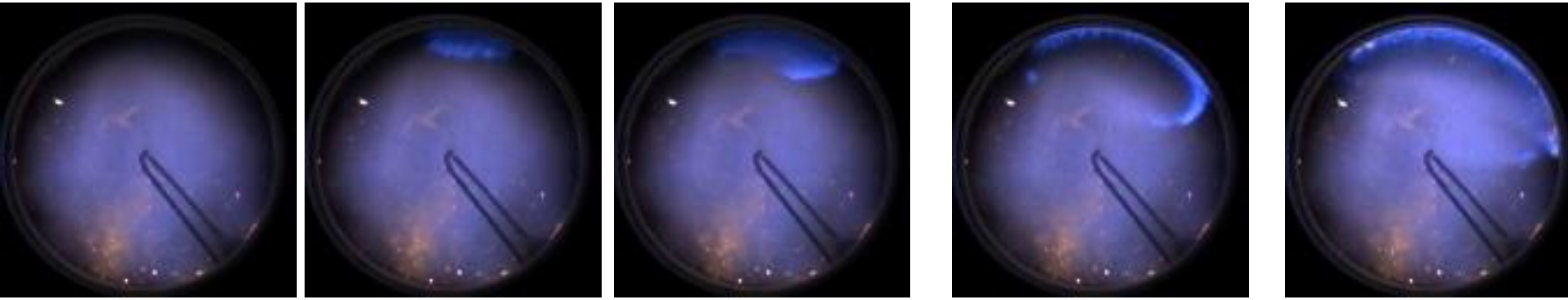
机械破坏

用直接数值模拟揭示“近壁起爆”过程

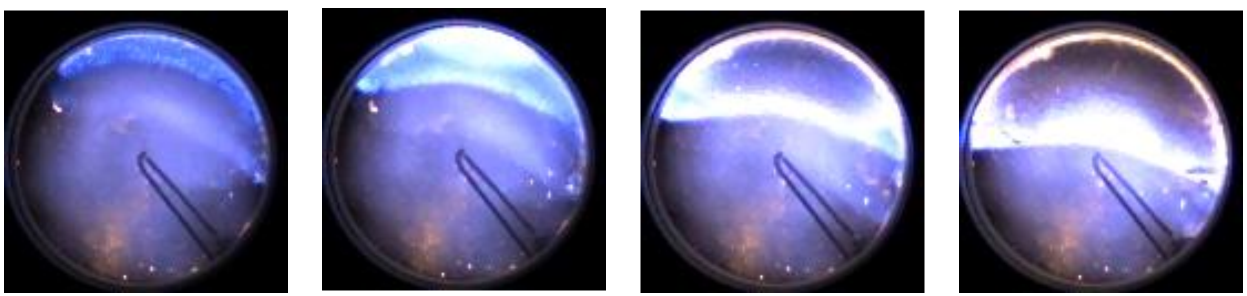
SWRID(shock wave reflection induced detonation)

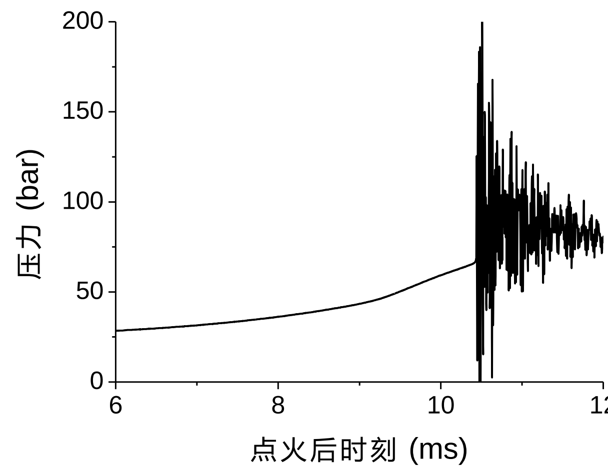


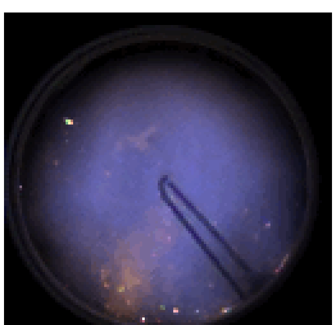
超级爆震为什么能一个循环破坏发动机？



图像间间隔1/288000 s

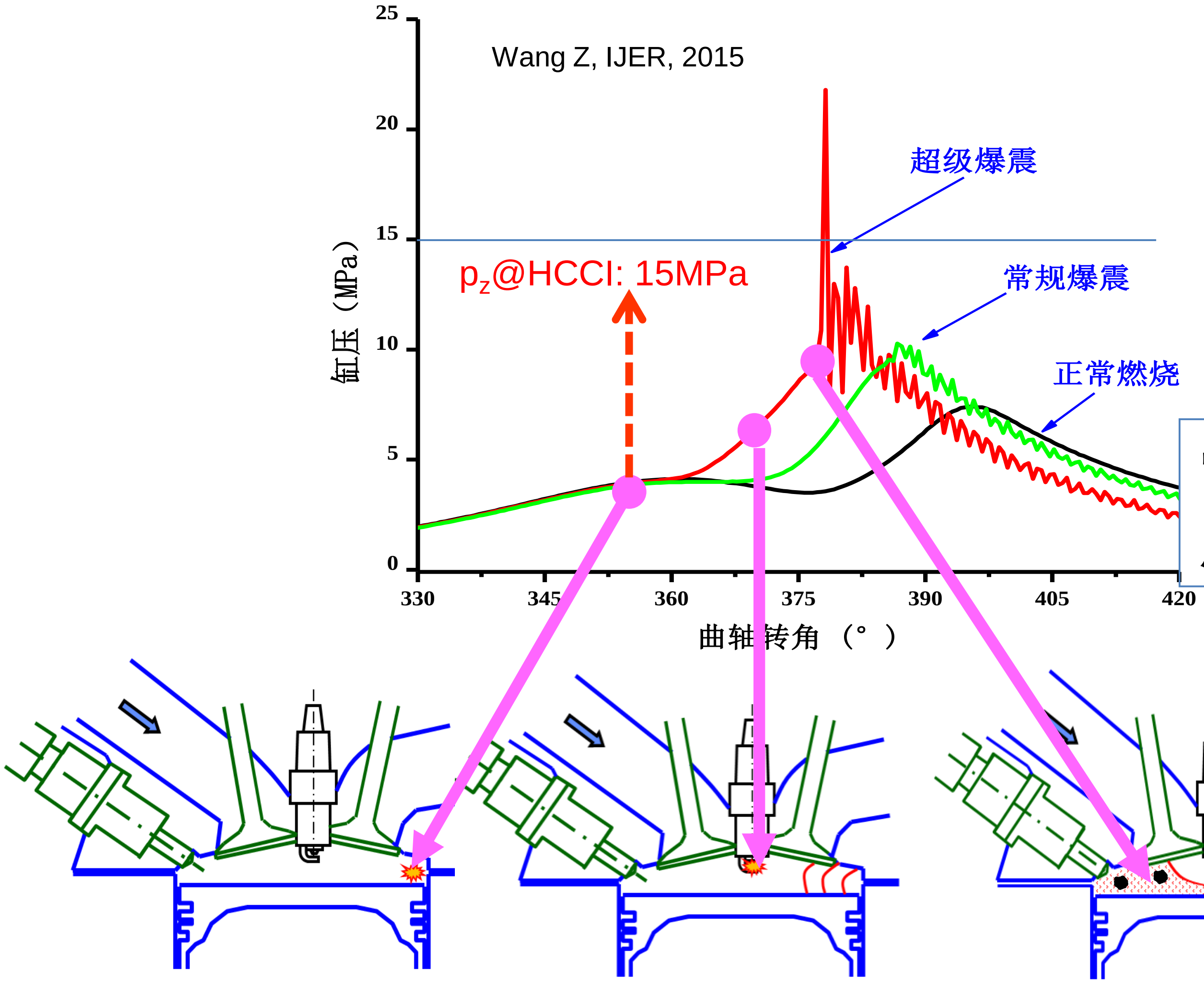






石英表面裂纹

超级爆震为什么能诱发极高的缸压？



常规爆震：火花点火之后出现末端混合气自燃

超级爆震发生，不仅与早燃有关，而且与早燃发生后燃烧模式有关

主要内容

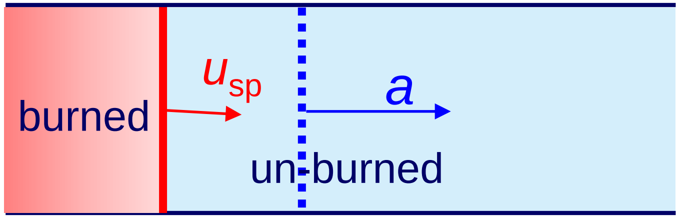
1. 内燃机爆震燃烧过去的工作
2. 国际进展及前沿与难点问题
3. 未来可能的研究方向与合作

Spontaneous propagation(SP) modes

Zeldovich classified auto-ignition/SP into four modes:

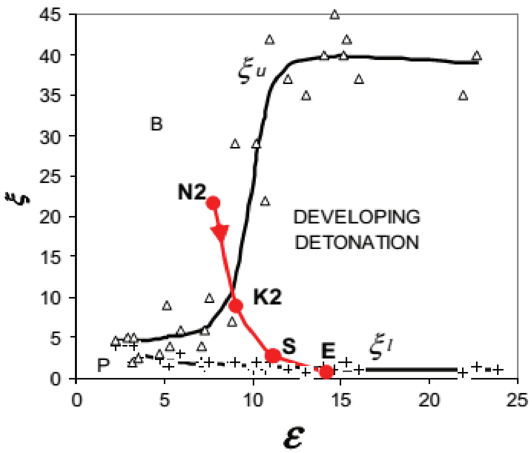
1) Near thermal explosion without shock wave: $u_{sp} > D_{cj} >> a$
2) Detonation propagating supersonically: $D_{cj} \geq u_{sp} > a$
3) Spontaneous ignition propagating subsonically: $a > u_{sp} > u_f$
4) Normal flame propagating by molecular diffusive and conductive mechanisms: $u_{sp} \cong u_f$

- Spontaneous propagation speed: u_{sp}
- Chapman-Jouguet Detonation speed: D_{cj}
- Sound speed: a
- Laminar flame speed: u_f

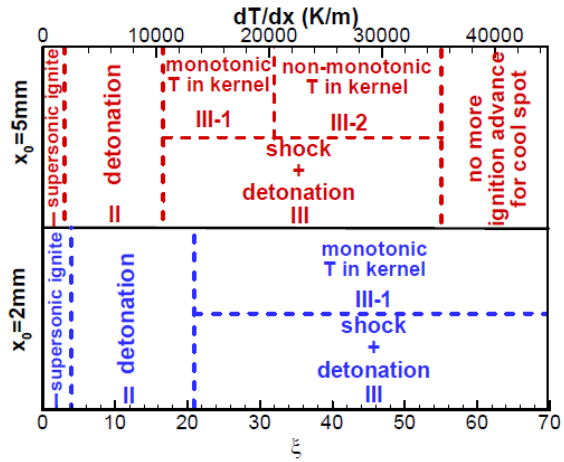


Ya. B. Zeldovich. Regime classification of an exothermic reaction with nonuniform initial conditions. Combustion and Flame 39: 211-214 (1980).

Numerical simulation on super-knock

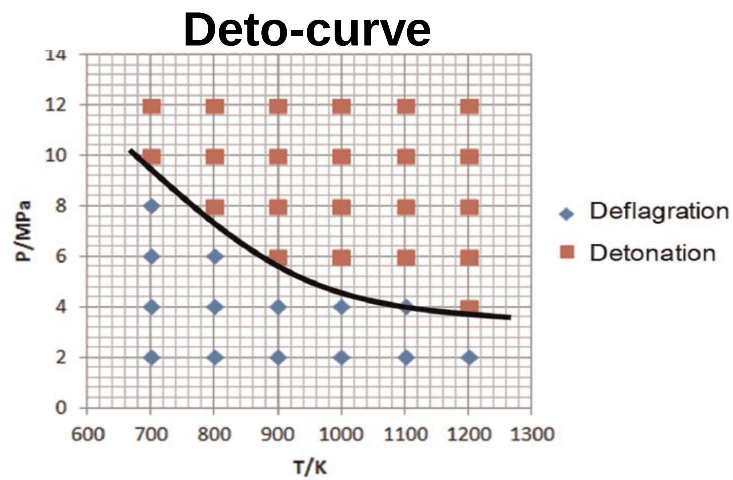


Bradley, Kalghatgi, SAE 2002; IJER, 2012



Dai P, Chen Z. PCI 2015

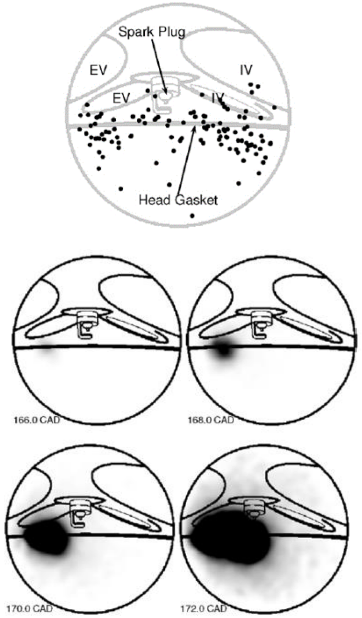
Dai P, Chen Z. CNF2015



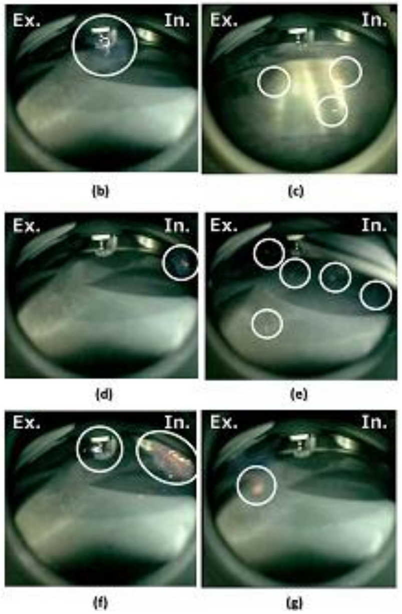
Wang Z, IJER, 2014

- In 2002, Gu- Bradley extended AI theory by T gradient. 2012, Kalghatgi -Bradley applied this method in TC-GDI, showed super-knock in "developing detonation" .
- Dai - Chen numerically simulated the reaction front propagation in n-heptane /air mixture with cold spot, several auto-ignition modes were identified.
- Wang - He studied iso-octane under the high-T,P. When unburned mixture state reaches above Deto-curve, the hot-spot could induce detonation.

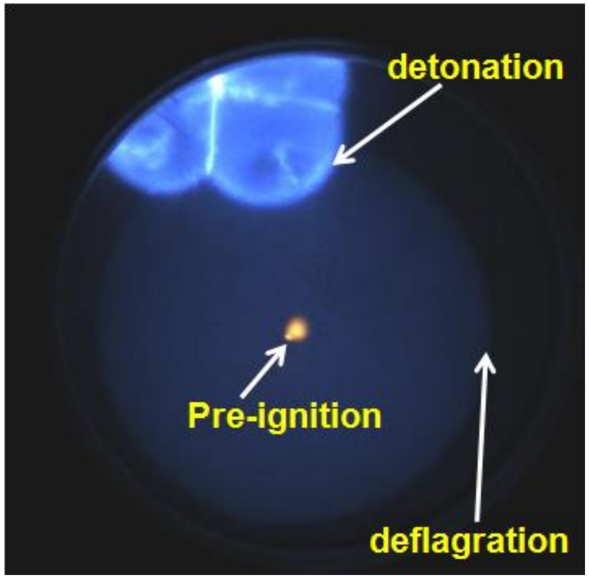
Optical investigations on super-knock



Dahnz. SAE 2010-01-0355



Okada Y, SAE 2014-01-1218



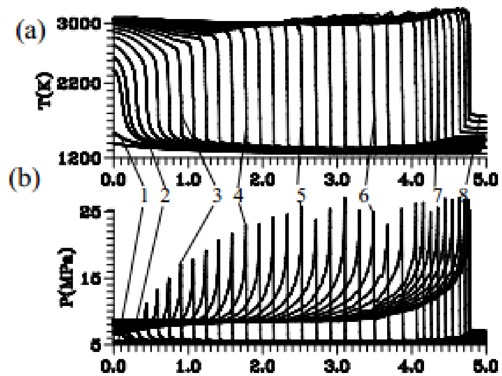
Wang Z, Fuel .144 (2015) 222–227

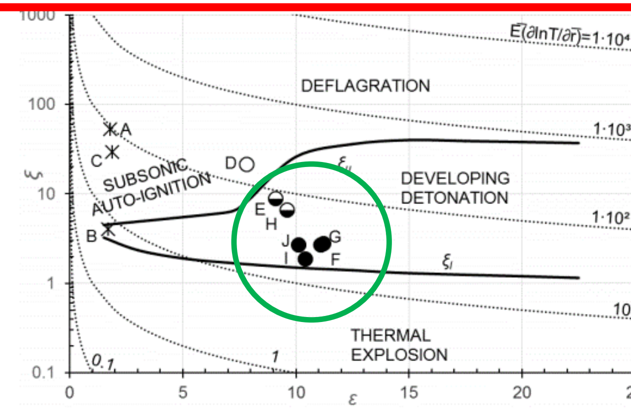
- Previous studies on super-knock using endoscope, the visualization gives good explanation of the possible sources of pre-ignition.
- Difficult to investigate the transition from pre-ignition to super-knock (PI-SK) on optical engine due to the strength and the size of viewing field.
- This difficulty can be circumvented by using a RCM to simulate conditions similar to ICEs, and providing excellent optical accessibility.

1）热点说

Bradley

Engine Hot Spots: Decay, Deflagration, Auto-Ignitive Propagation, or Detonation ?





“热点”说——爆轰形成取决于温度梯度，是温度梯度（热点）和活性耦合

[SAE2002,CNF2009, ICDERS 2015]

Engine	Fuel	Auto-ignitive mode	Fig. Ref.	φ	T K	P MPa	$\overline{E}$	Ref.
1. Hydra single cylinder with Roots blower	PRF 84 [5,17,19]	Controlled benign MILD auto-ignition.	A	0.25	729	6.52	6,799	[18,6]
			B	0.25	811	4.84	543	
			C	0.25	1057	3.37	5,829	
2. Turbo-charged S.I. engine (GM Powertrain)	RON/MON 95/85, OI=105. Surrogate 0.62 *i*-octane, 0.29, toluene, 0.09 *n*-heptane, OI=105 [5]	No auto-ignition	D	1.0	800	7.0	13,269	[21]
		Fairly heavy knock	E	1.0	850	9.0	6,716	[21]
		Pre-ignition, super-knock	F	1.0	926	12.8	2,696	[21]
3. Turbo-charged S.I. engine (VW)	RON/MON 98/89, OI=107. Surrogate as above [5]	Pre-ignition, Super-knock	G	1.0	918	13.3	2,822	[22]
4. Turbo-charged S.I. engine (Tsinghua University, Beijing)	Composition in [24]. RON/MON, 94.1/81.9. Data for 93.4/81 from [5,18].	Slight knock	H	1.0	824	10.45	5,229	[23,24]
		Super-knock, deflagration	I	1.0	949	10.91	1,906	[23,24]
		Super-knock, detonation	J	1.0	917	10.5	2,467	[23,24]

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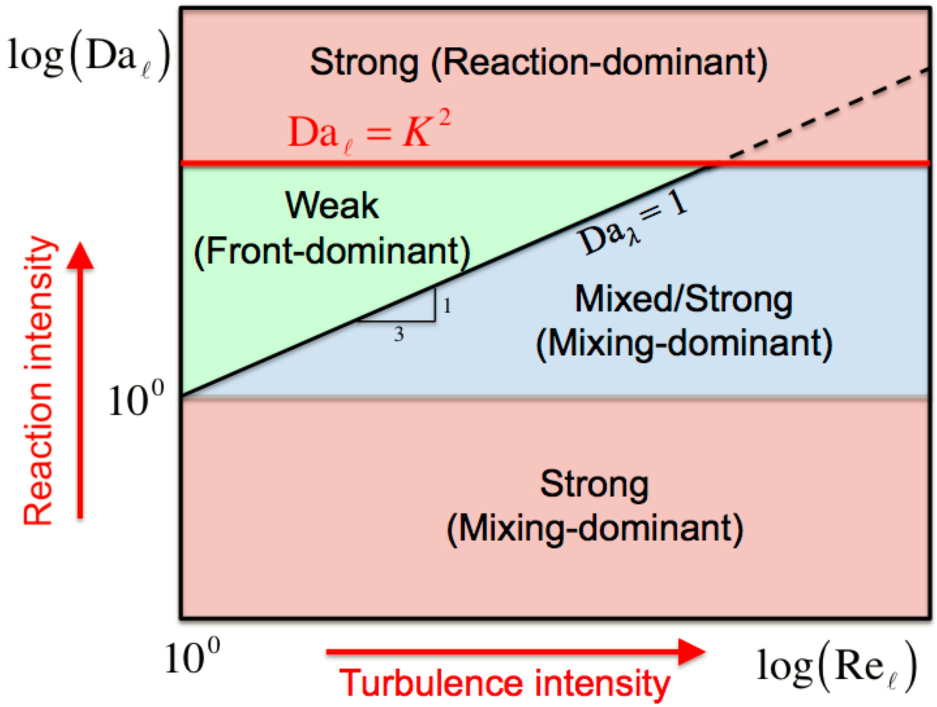
2）湍流说

"湍流"说——爆轰形成受控于湍流混合，是湍流混合与活性耦合[CST 2015]



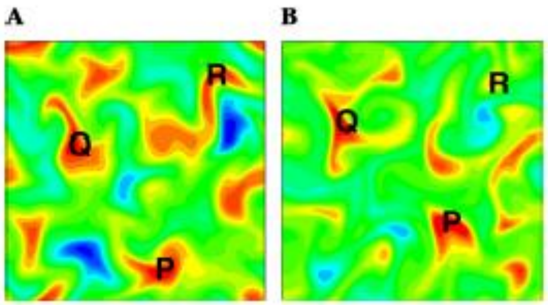


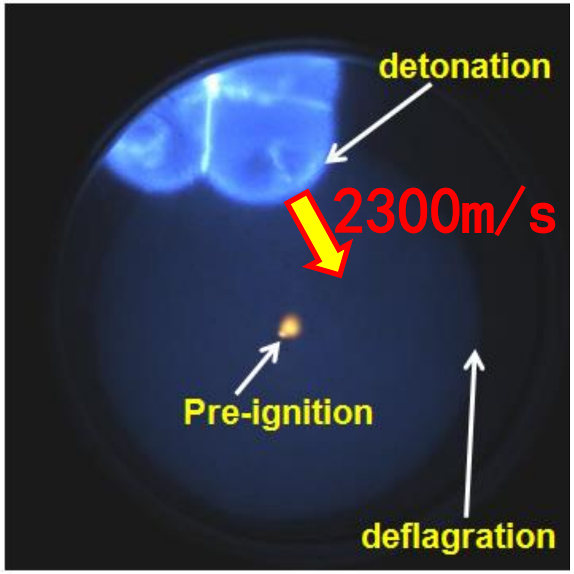
Fig. 2. Instantaneous temperature isocontours for Case A at (A) 0.4 ms and (B) 1.5 ms.

- 密西根大学的Sankaran等和Sandia实验室的Chen在Zeldovich[1]基础上，定义出无量纲参数Sa（层流火焰速度和自燃速度之比），用于判断未燃混合气的燃烧模态。通过二维直接数值模拟研究认为，Sa数可用做区分大面积自燃和局部火核触发的火焰传播两种燃烧模态的判定准则。

3）激波说

“激波”说——爆轰形成起源于激波交汇，是激波压缩和化学活性（化学放热）耦合

[王建昕，王志，何鑫（2012E&F, 2014 IJER, 2014 FUEL、2015 CNF, 2015CST, 2015 ICDERS）,陈正(2014PCI, 2015CNF)，姚春德(2015ECM)，卫海桥(2015 IJHE)等]。



Wang et al. 11

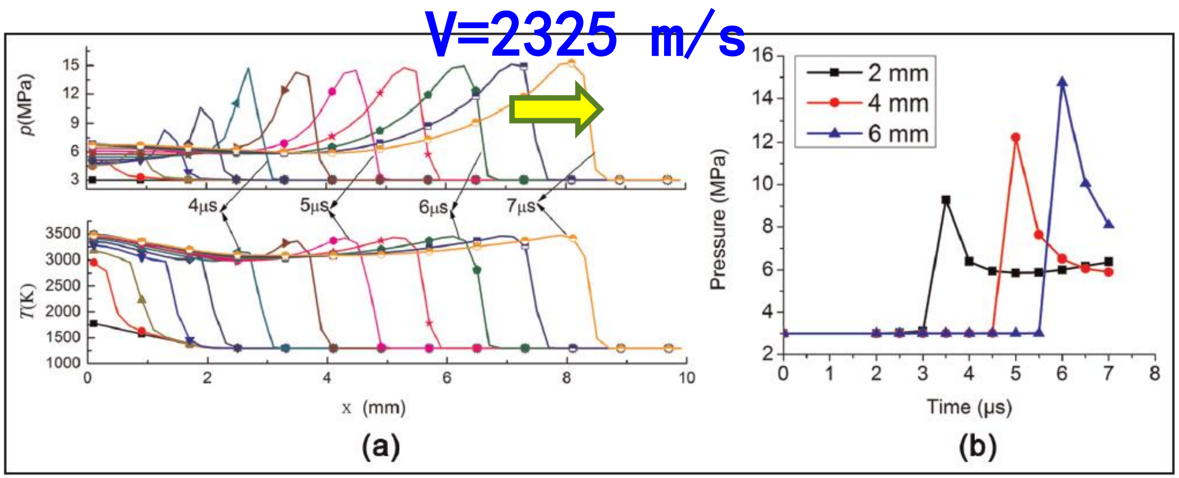


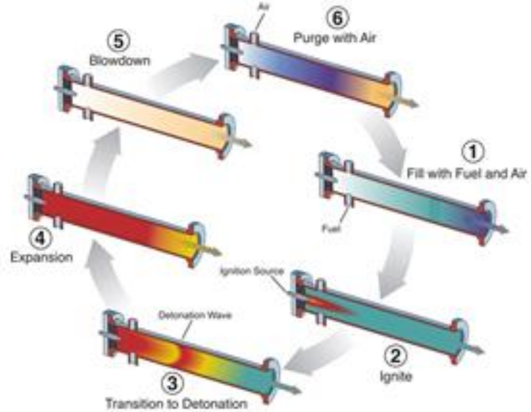
Figure 17. Hot-spot-induced detonation: (a) pressure and temperature evolution and (b) pressure history at different positions (p_{in} = 3 MPa and T_{in} = 1300 K, stoichiometric condition).

主要内容

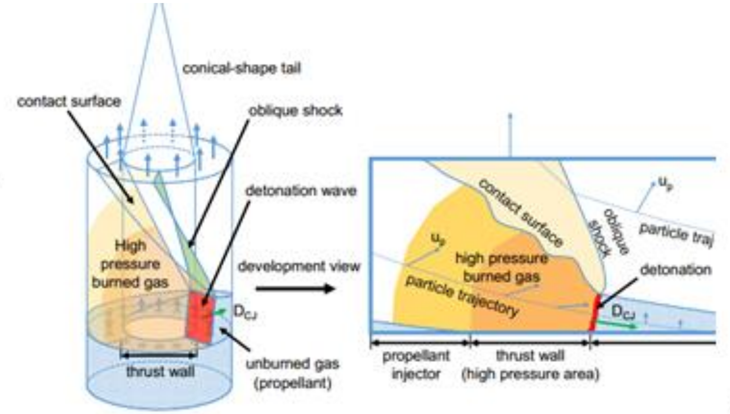
1. 内燃机爆震燃烧过去的工作
2. 前沿与难点问题及国际进展
3. 未来可能的研究方向与合作

爆震燃烧是先进发动机燃烧的共性问题

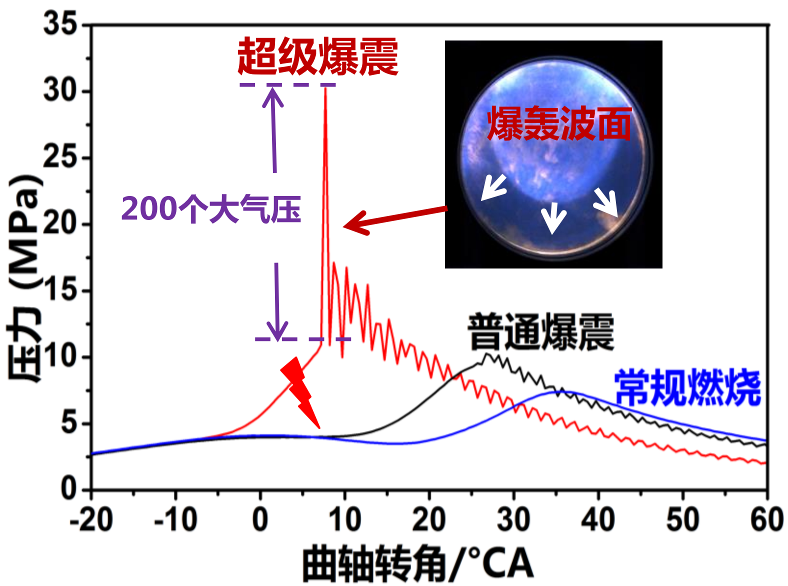
汽车发动机（点燃式）



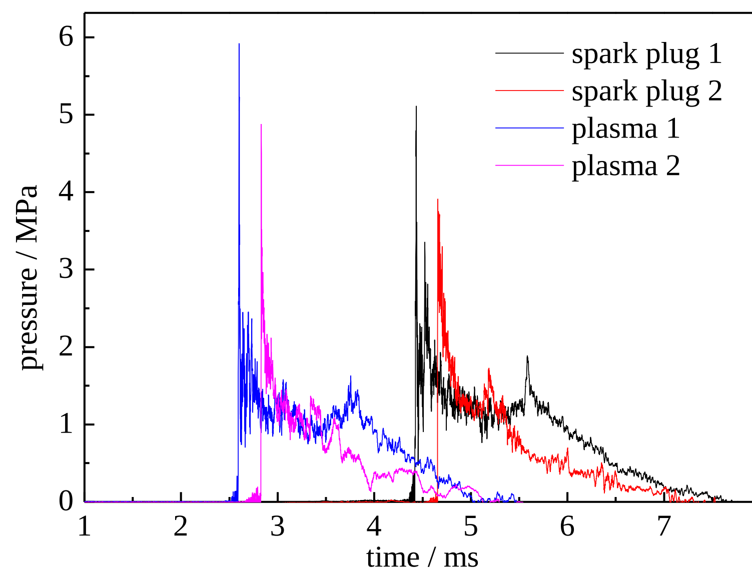
脉冲爆震发动机（PDE）



旋转爆震发动机（RDE）



a) 内燃机(3MPa-30MPa)

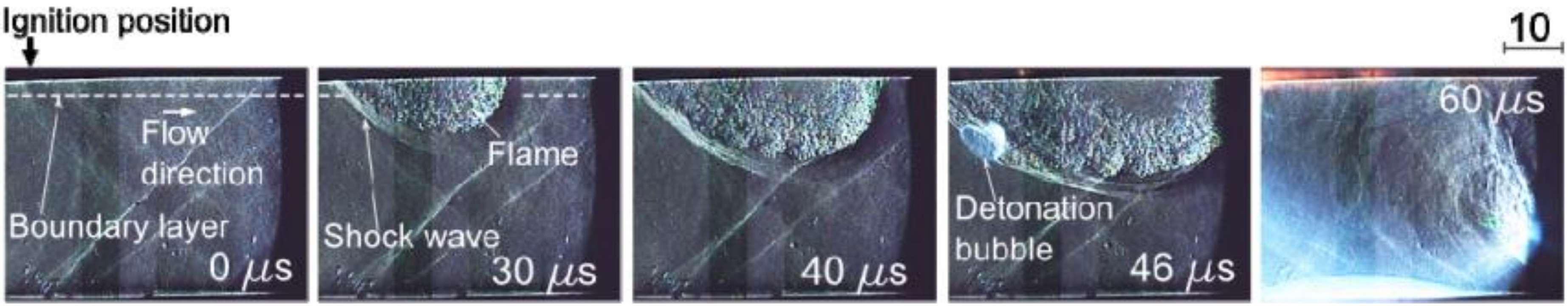


b) 爆震发动机(0.1MPa-10MPa)

发动机中爆震燃烧现象

研究方向1：爆震燃烧起爆机制

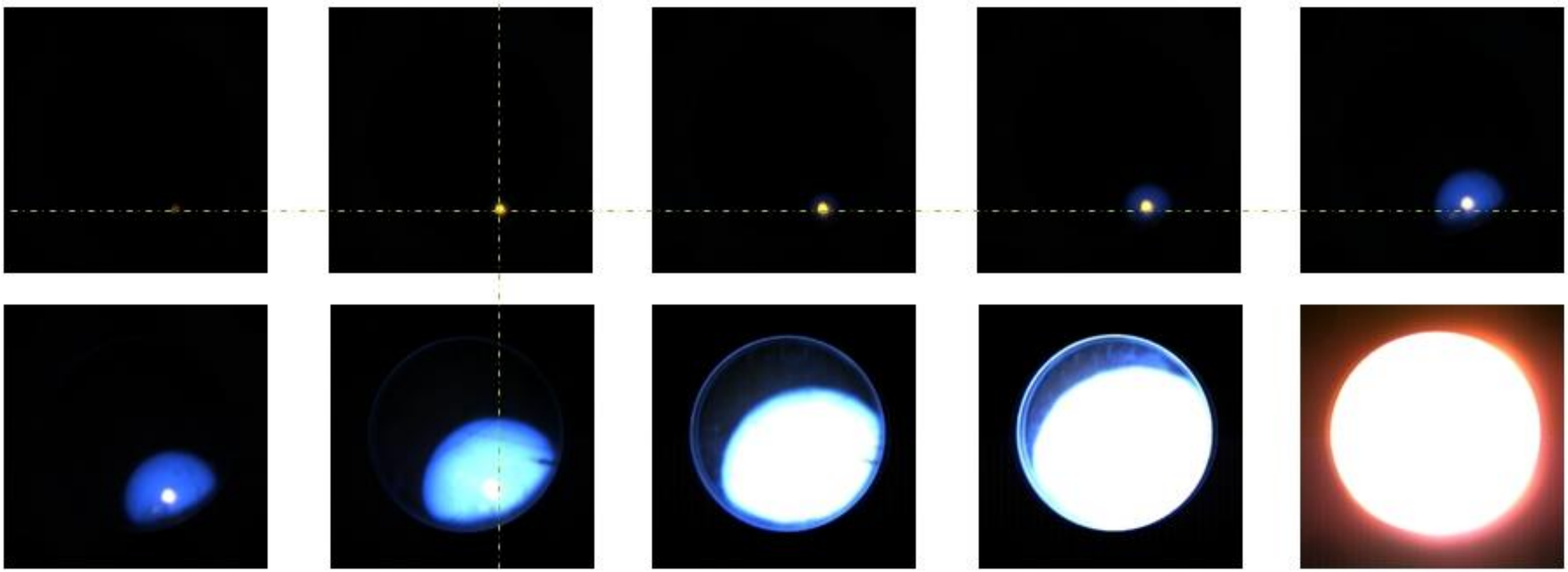
- 爆震燃烧是极端条件下燃烧问题，涉及从热点到爆燃/爆轰/热爆炸的多种燃烧模态、多种起爆模式。
- 决定爆震起爆控制因素虽多，但可以确定的是：爆轰与混合气活性相关，不论是温度的自然分层，还是湍流的随机性，还是激波压缩，都可能产生起爆。但目前量化的条件不明确、湍流-激波-活性基间如何相互作用，亟待进一步研究。



一维爆震腔中的DDT起爆过程的高速摄影[Ishihara, ICDERS 2015]

研究方向2：可燃混合气中单（多）颗粒点火和火焰发展机制（粉尘爆炸）

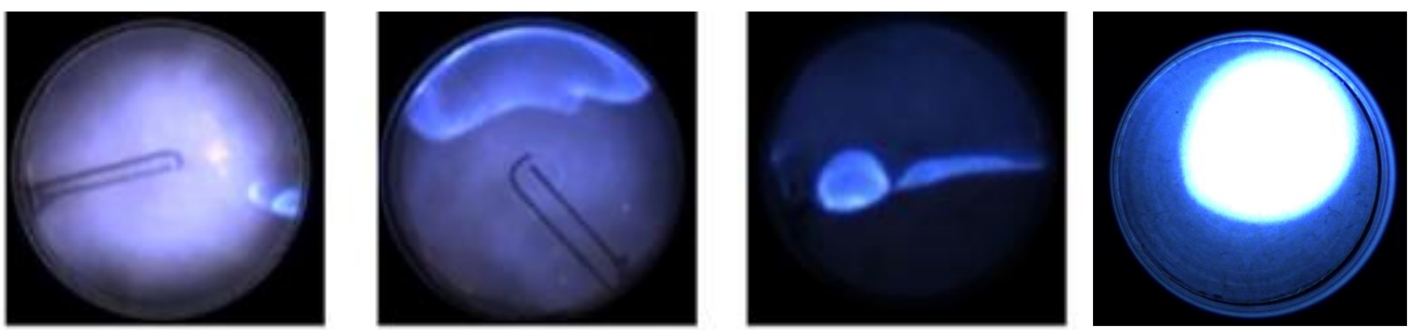
- 内燃机爆震燃烧目前主要集中在鉴别早燃源，减少超级爆震频次。对早燃源的点火机制和早燃后如何产生超级爆震并未深入研究。



正在进行…

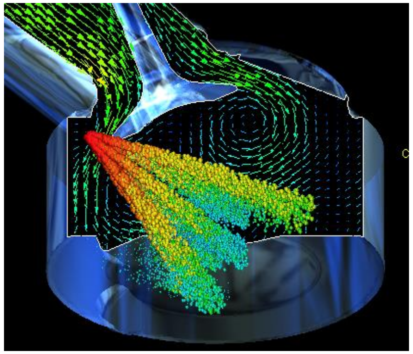
研究方向3：爆震燃烧的调控

- 爆震燃烧调控方法方面，还缺乏有效抑制爆轰/稳定利用爆震的实用方法。
- 学术思想是：要抑制/促进爆轰，根源在与于将激波（shock wave）和反应面（ignition front）解耦/耦合。可以通过改变激波强度和方向、混合气的空间浓度和活性分布等入手。



a) 激波壁面反射起爆　　b） DDT　　c) 空间直接起爆

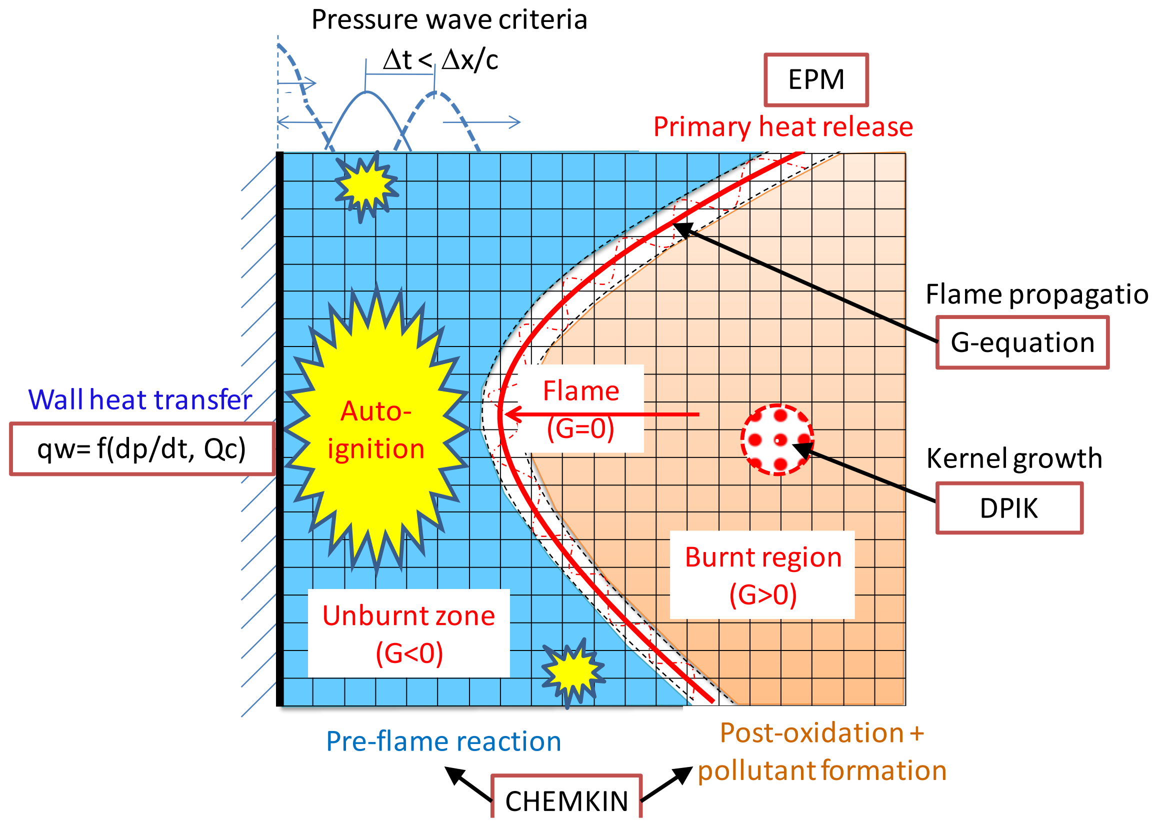
不同温度和压力条件下的典型起爆模式



喷雾浓度和活性分层抑制爆震

研究方向4：爆震燃烧传热模型

- 爆震燃烧工况下，容易出现活塞烧顶等热负荷问题，还缺乏高精度高计算效率**爆震燃烧CFD传热模型**



考虑近壁自燃和压力震荡的传热模型

Acknowledge

- 感谢国家自然科学基金和清华大学自主课题的支持。
- 感谢国内同行有意义的讨论！

谢谢大家！

敬请批评指正！