WEICHAI 潍柴

北京工业大学 BEIJING UNIVERSITY OF TECHNOLOGY

第十一届内燃机可靠性技术国际研讨会

高压气体燃料直喷射流及湍流燃烧特性

Performance of high-pressure gas fuel direct injection and turbulent combustion

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目　录

一.气体燃料缸内直喷技术Gas fuel direct injection technology

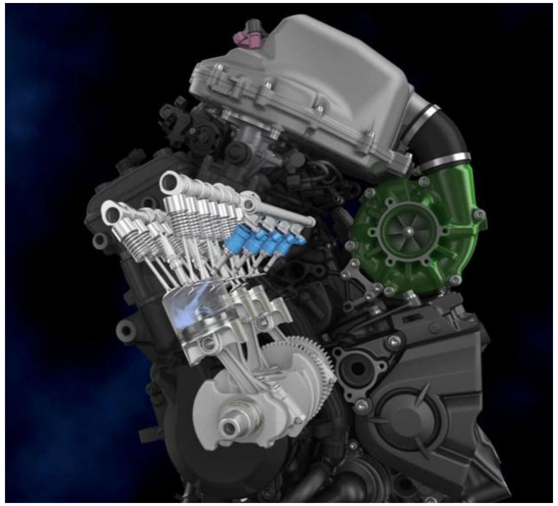
低碳气体燃料是发展方向
Low-Carbon gas fuel is future direction.

缸内直喷技术是必然路线
DI is the inevitable development route for gas engine.

H_2 NH_3 NG

天然气直喷发动机
NG DI engine

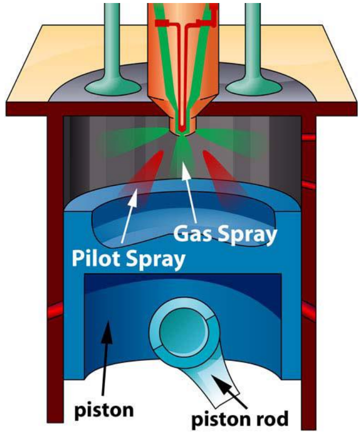
氢气直喷发动机
H2 DI engine



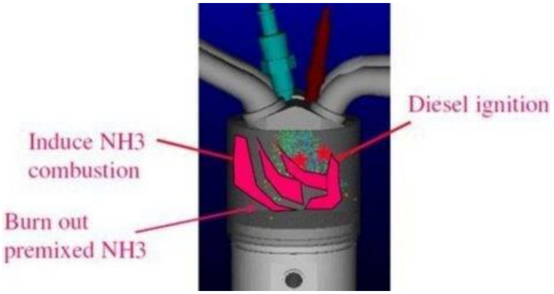
高压气体燃料缸内直喷技术
High pressure gas fuel DI

喷射压力injection pressure 200~300bar

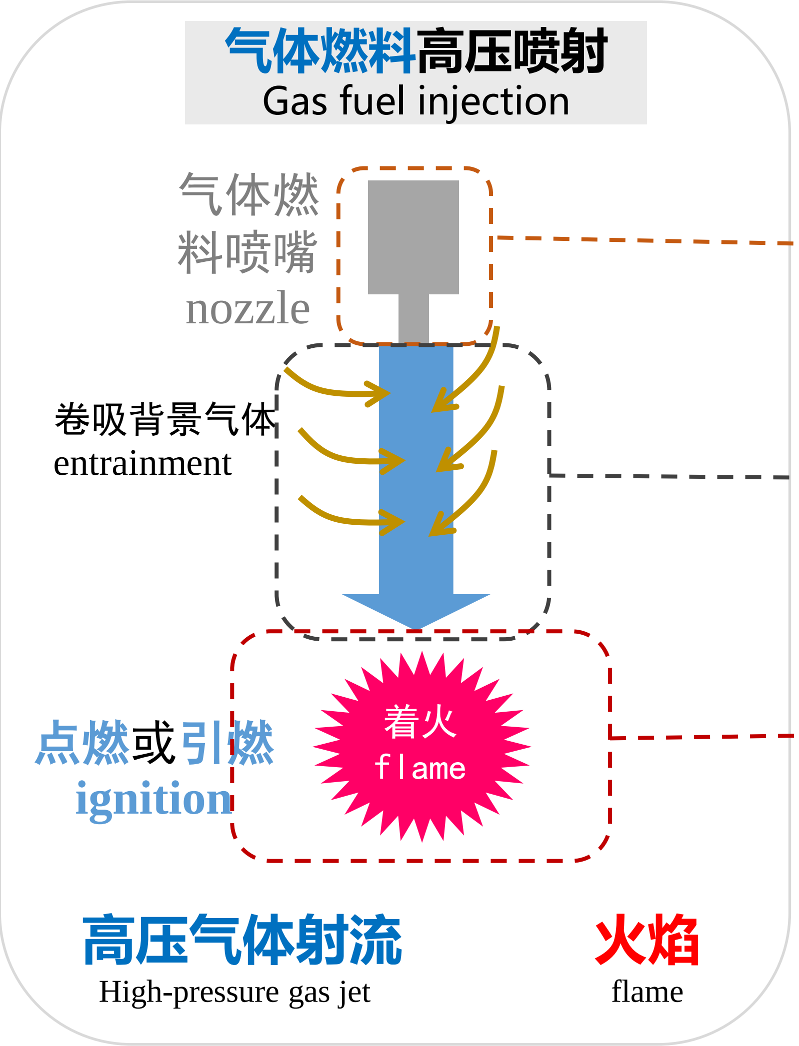
气体燃料缸内直喷具有瞬时动态、音速射流的特点
Gas fuel DI: dynamic, sonic jet



NG：HPDI



NH3：DI



- 喷嘴内流对射流的影响
  Effect of nozzle Inner flow on gas jet

- 气体射流过程卷吸特性
  Entrainment during gas jet
- 射流过程能量传递规律
  Energy transfer during gas jet

- 气体射流对预混火焰的作用
  Effect of gas jet on premixed flame

主要研究内容

Research content

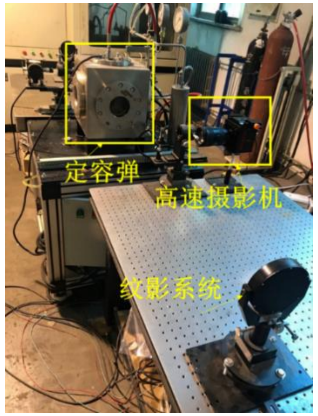
NG H2 NH3

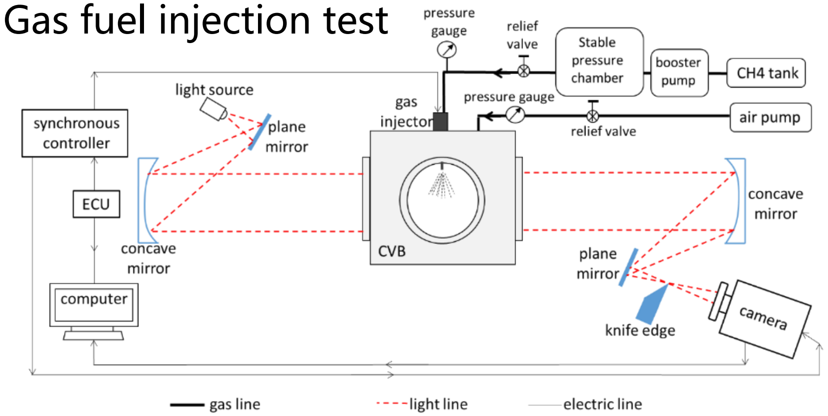
气体燃料：甲烷、氢气
Gas fuel: CH_4, H_2

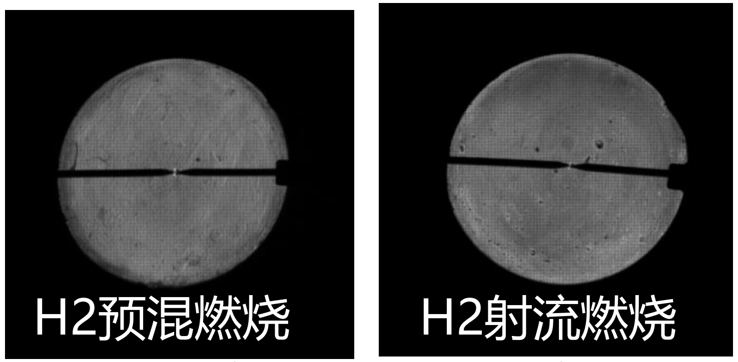
试验喷射压力test injection pressure~200bar，背压back pressure~20bar

气体燃料：氨气 喷射压力injection pressure ~8bar
Gas fuel : NH_3

气体燃料射流特性测试
Gas fuel injection test

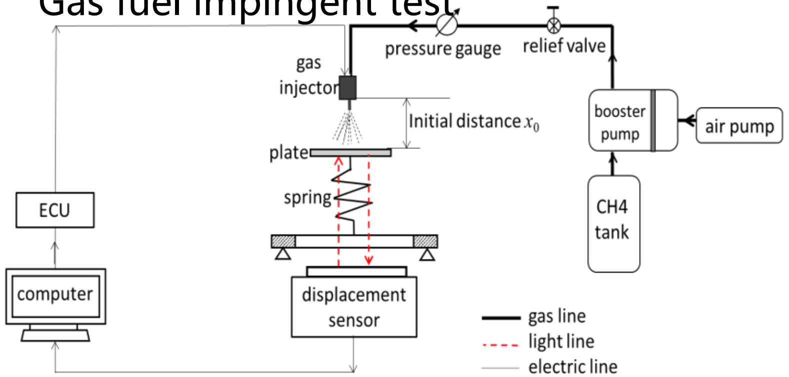




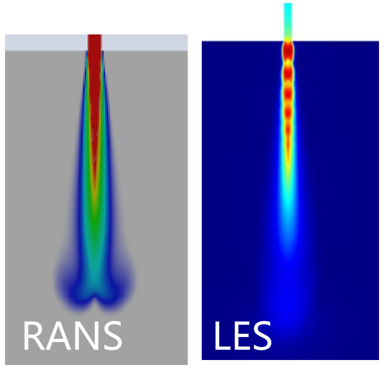


H2 premixed flame　　H2 jet flame

气体燃料冲击特性测试
Gas fuel impingent test

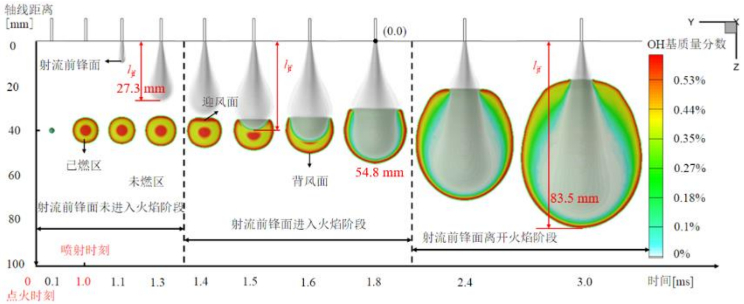


气体射流仿真



CFD of gas jet

射流燃烧仿真

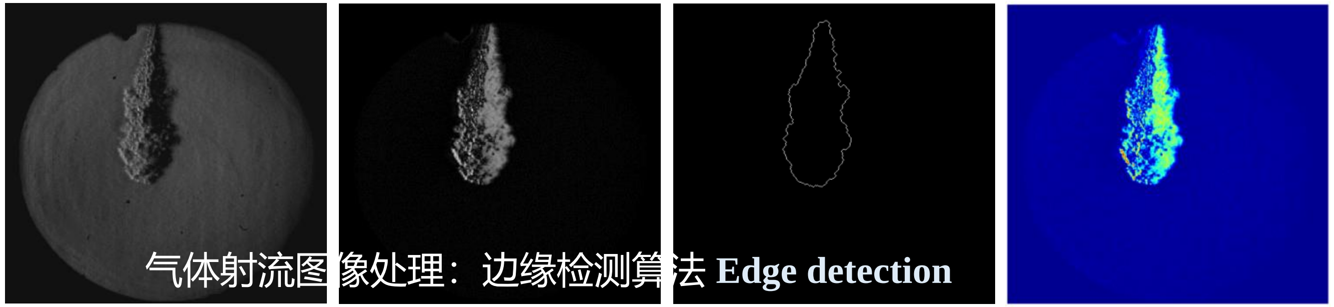


CFD of jet flame

图像处理方法

Image process method

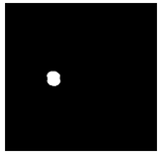
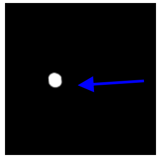
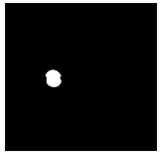
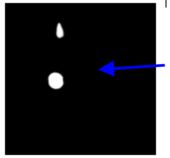
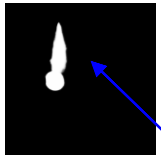
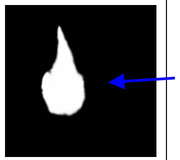
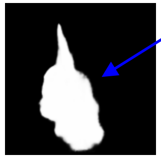
气体燃料直喷射流 Gas fuel DI jet



气体射流图像处理：边缘检测算法 Edge detection

气体燃料射流燃烧 Gas fuel jet flame

射流燃烧图像处理：深度学习算法 Deep learning

	边缘检测算法 Edge detection		深度学习法 Deep learning
0.1ms 预燃火焰		可以识别火焰	
0.3ms 射流出现		可以识别火焰，但无法识别射流	
0.6ms 射流接触火焰		射流边界未完全识别，存在背景杂质	
1.3ms 湍流燃烧		射流边界未完全识别，火焰轮廓不完整，存在背景噪声	
2.0ms 湍流燃烧		射流火焰边界未完全识别，火焰与壁面出现重叠，背景杂质多	

可以识别火焰

可以识别火焰、射流

可以识别火焰、射流，背景清晰

发现：

- ◆ 深度学习方法和边缘检测算法可完成图像处理。
- ◆ 边缘检测算法适合于单一目标的火焰图像处理。
- ◆ 深度学习方法可以识别射流湍流燃烧火焰轮廓，适用于多个目标的火焰图像处理。

Publications

1. 石磊,雷艳,等.基于深度学习的甲烷高压射流湍流燃烧火焰图像处理方法研究.内燃机工程,2022,43(04):22-30.

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目 录

二. 高压气体燃料直喷射流特性研究

Study on high-pressure gas fuel direct injection

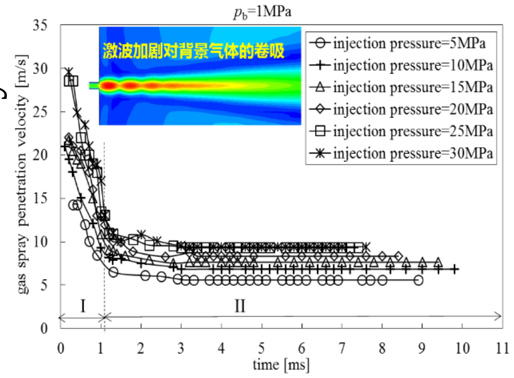
1.喷嘴内流对射流的影响

Effect of nozzle inner flow on gas jet

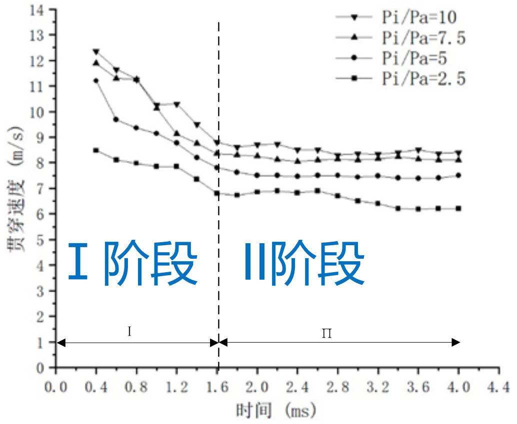
高压气体燃料直喷是音速射流，近嘴端区域出现激波，其喷射过程是一个**动态过程**，其动态特征主要受高压气体喷嘴内的流动引起的。

High-pressure gas direct injection is sonic jet with shock waves near the nozzle. The gas jet is dynamic which is induced by the nozzle inner flow.

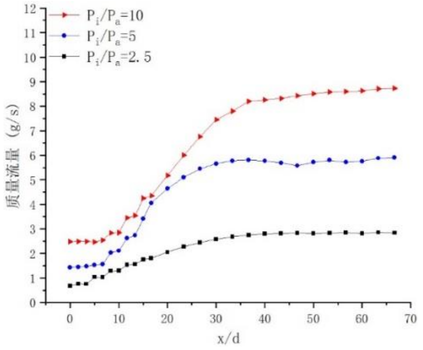
velocity



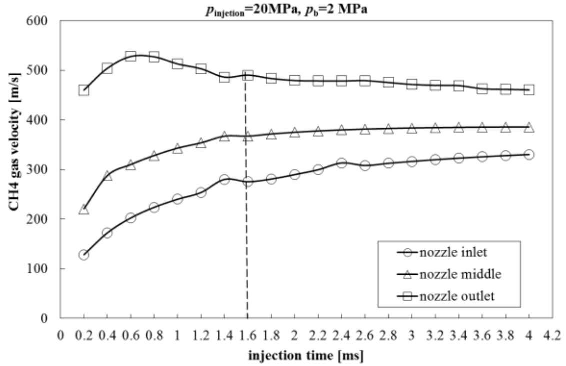
射流贯穿速度 gas jet velocity

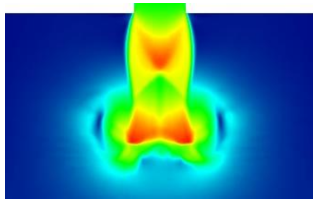


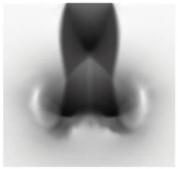
射流卷吸质量 Entrainment mass flow rate

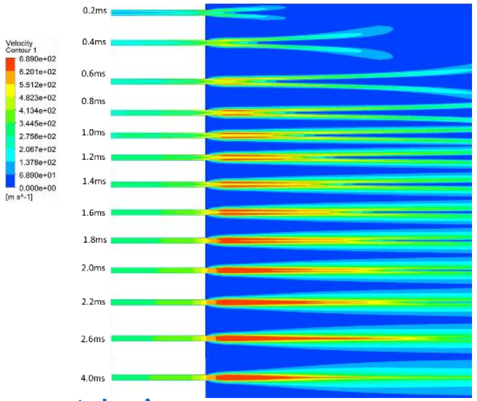


喷嘴内甲烷速度 Inner flow speed

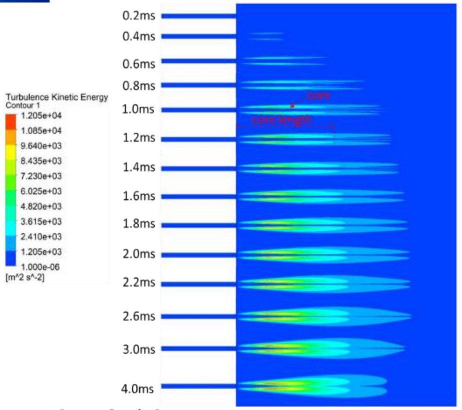








速度 Velocity



湍动能Turbulent Kinetic energy

Publications

2. Yan Lei, J. Liu, Tao Qiu, et al. Gas jet flow characteristic of high-pressure methane pulsed injection of single-hole cylindrical nozzle. Fuel, 2019, 257: 116081. (SCI)
3. 仇滔,万波,雷艳,等.高压甲烷圆形喷嘴的射流特性仿真.内燃机学报,2020,38(04):320-325. (EI).

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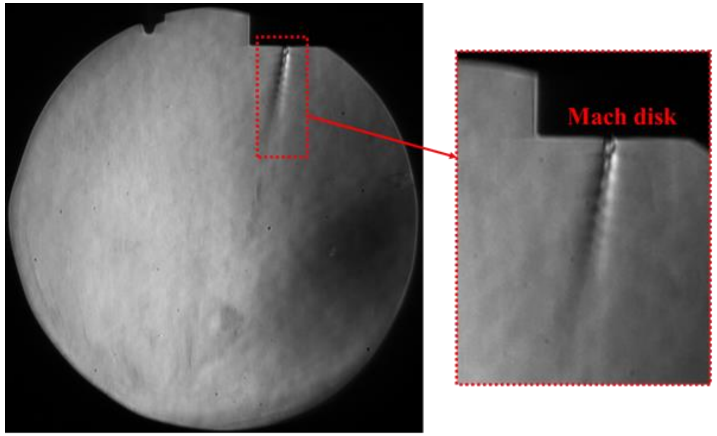
Study on high-pressure gas fuel direct injection

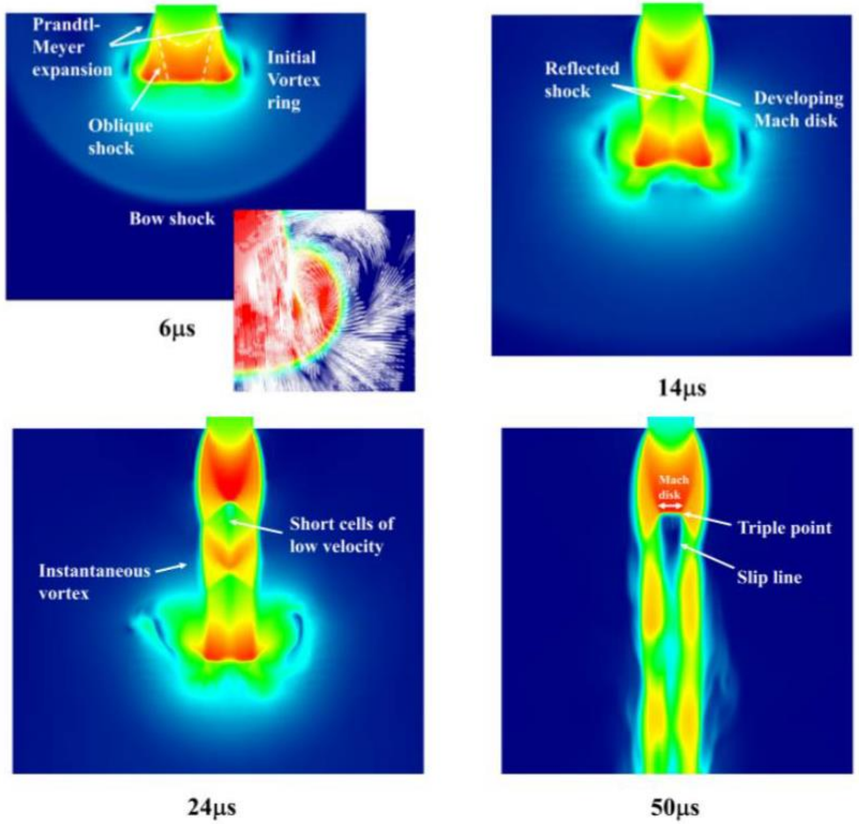
1.喷嘴内流对射流的影响

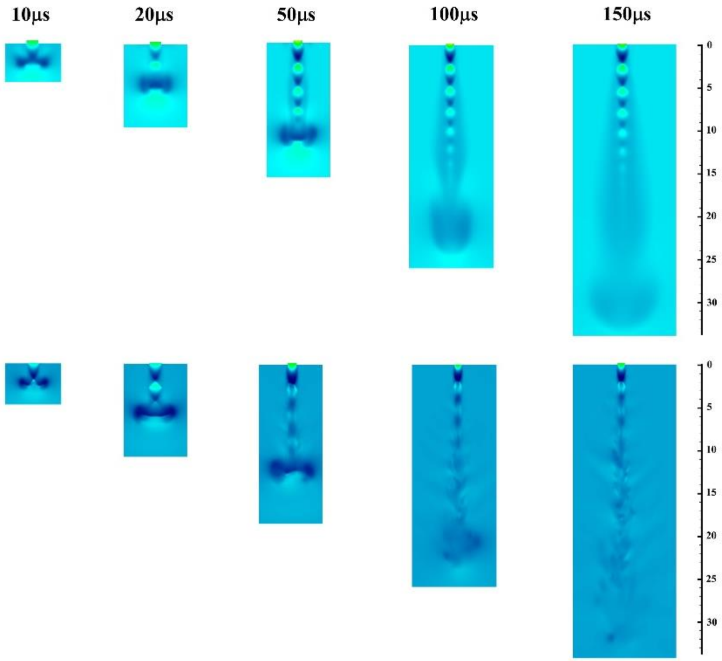
Effect of nozzle inner flow on gas jet

喷嘴出口附近马赫盘出现

Mach disk appears close to the nozzle outlet.







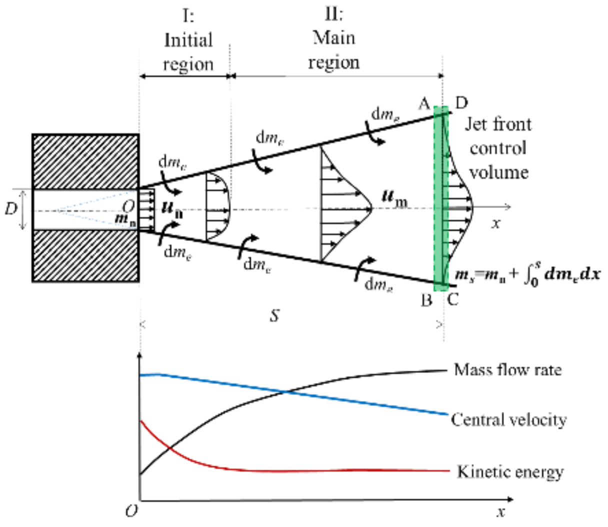
二. 高压气体燃料直喷射流特性研究

Study on high-pressure gas fuel direct injection

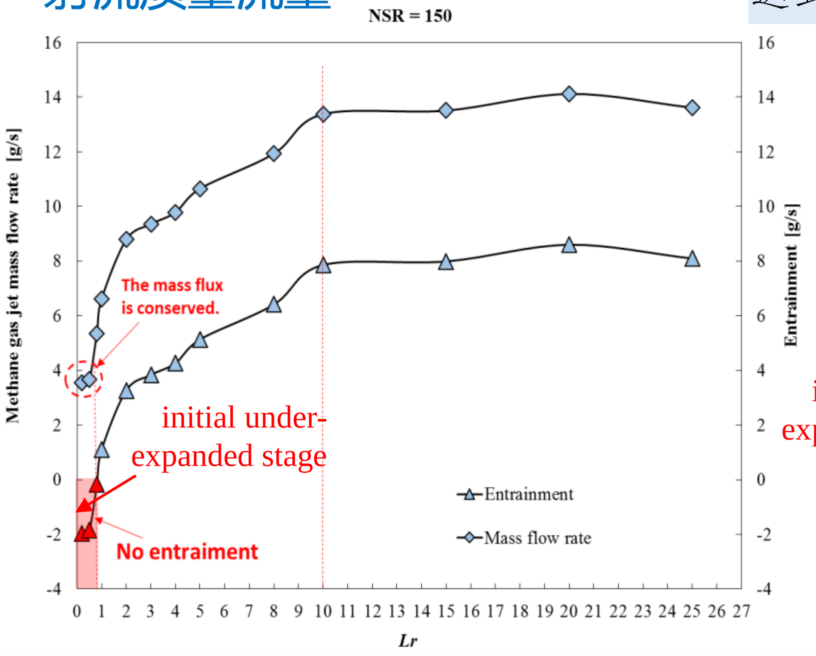
2.气体射流过程卷吸特性

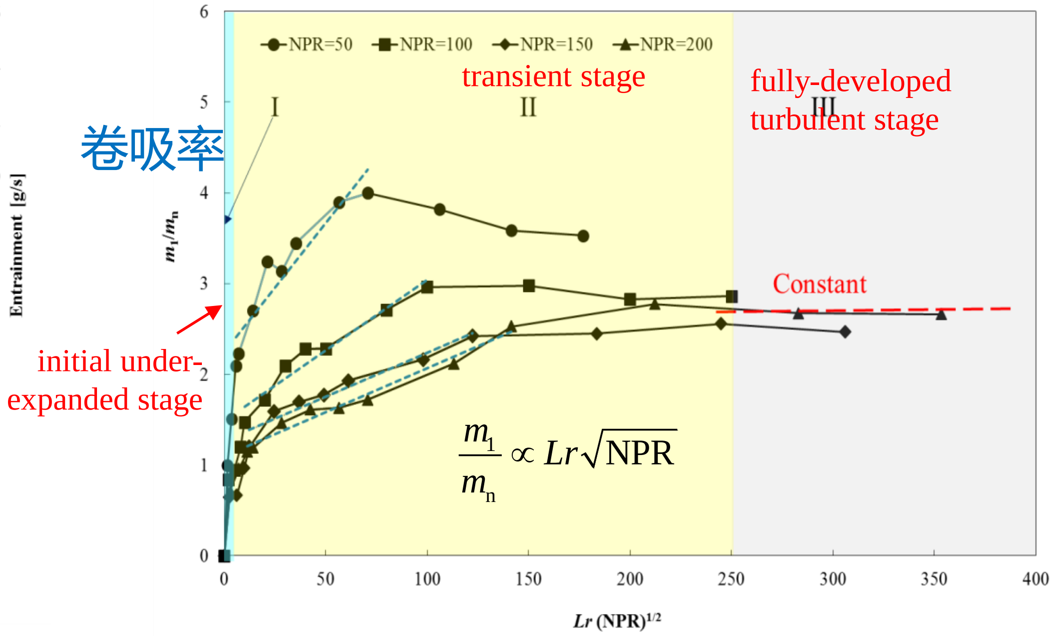
Entrainment performance during gas jet

高压气体燃料射流卷吸过程具有三段式(3-stage)特点，近嘴端区域（initial under-expanded stage）无卷吸(zero entrainment)，核心段区域（transient stage）卷吸能力最强(maximum entrainment)，远嘴端（fully-developed turbulent stage）卷吸达到饱和(saturated entrainment）。



射流质量流量





Publications

4. Yan Lei, Kai Chang, Tao Qiu, et al. Experimental Study on Entrainment Characteristics of High-Pressure Methane Free Jet. ACS Omega, 2022, 7(1), 381-396. (SCI)
5. 仇滔，常凯，雷艳，等. 一种基于动能法测量高压气体射流质量流量的方法和装置，专利号：ZL201910616060.9，2020-07-31授权（发明专利）
6. 雷艳，吴悦，仇滔，李泳. 一种测量气体音速射流卷吸的质量流量方法，专利号：ZL 201911049761.5, 2021-3-16授权（发明专利）

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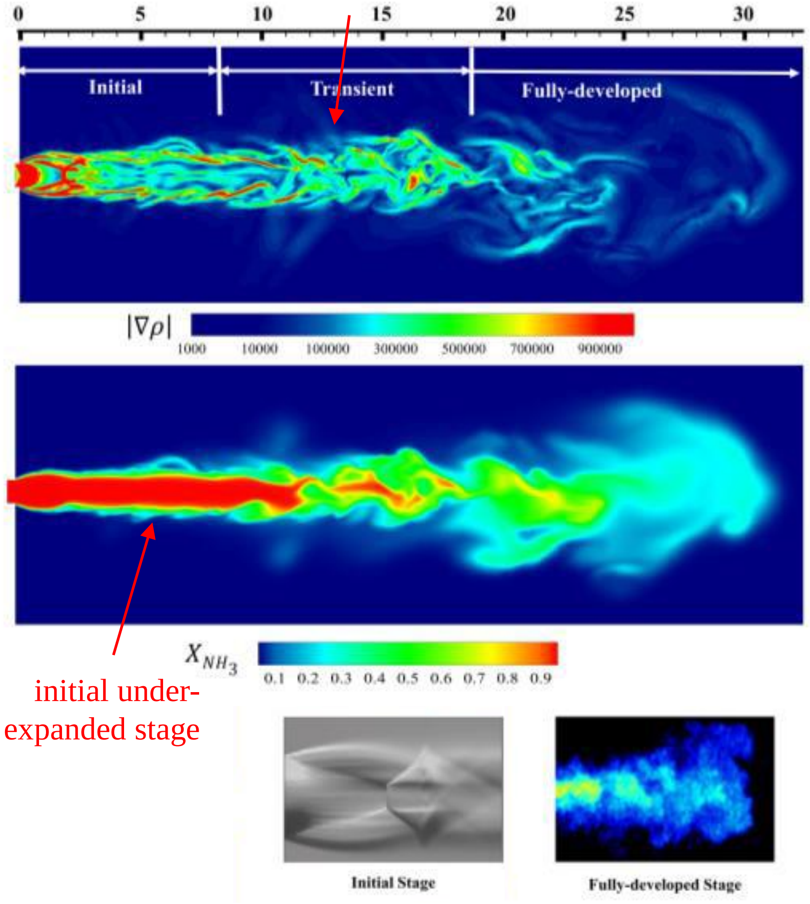
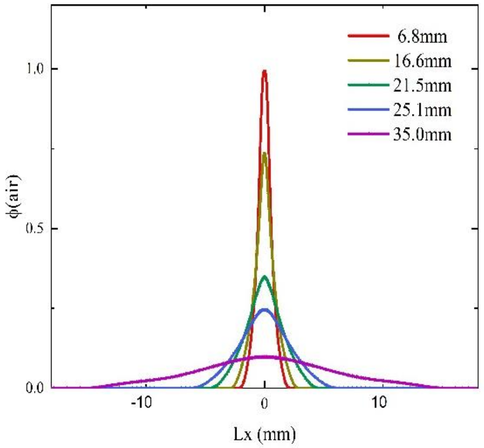
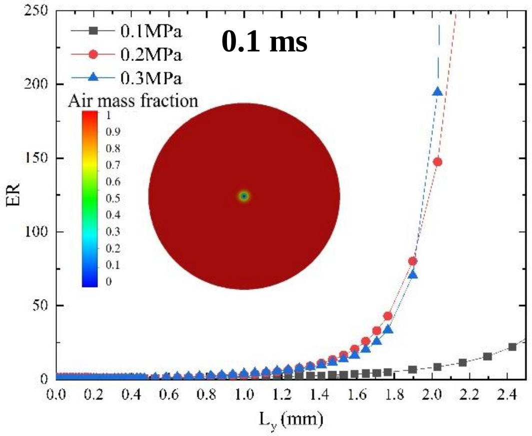
transient stage

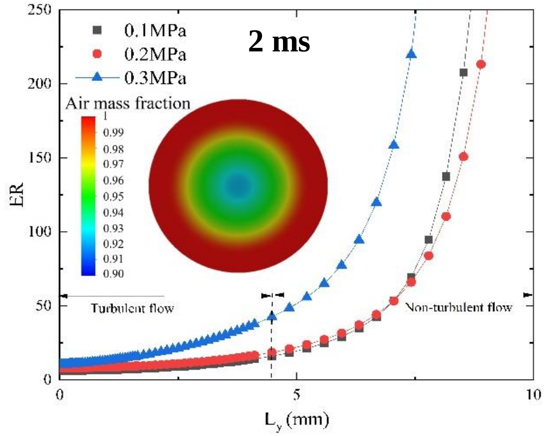


initial under-expanded stage

maximum entrainment in transient stage







Zero entrainment in initial stage

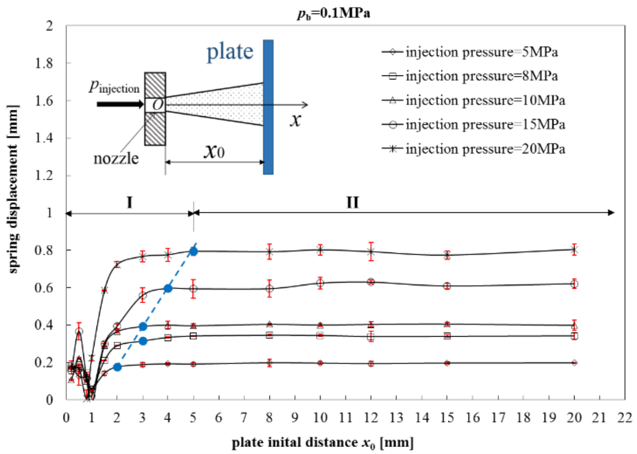
三. 高压气体燃料直喷射流特性研究

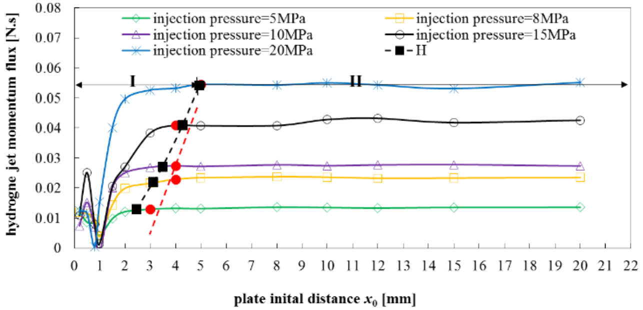
Study on high-pressure gas fuel direct injection

3.射流过程能量变换规律

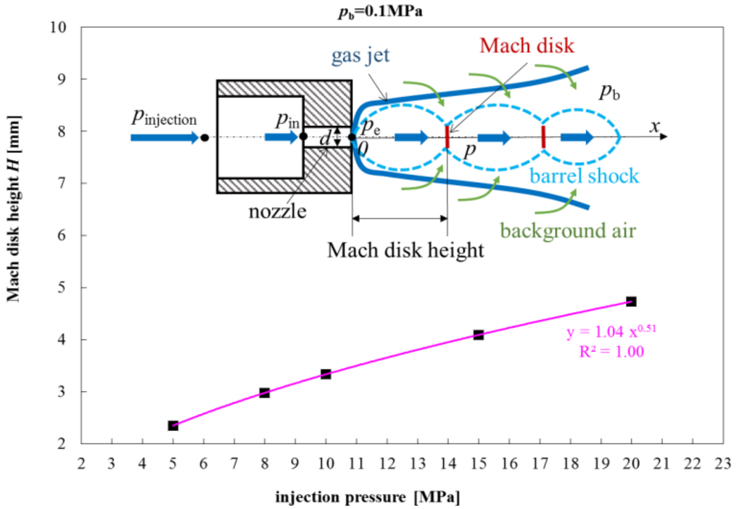
Impingent energy during gas jet

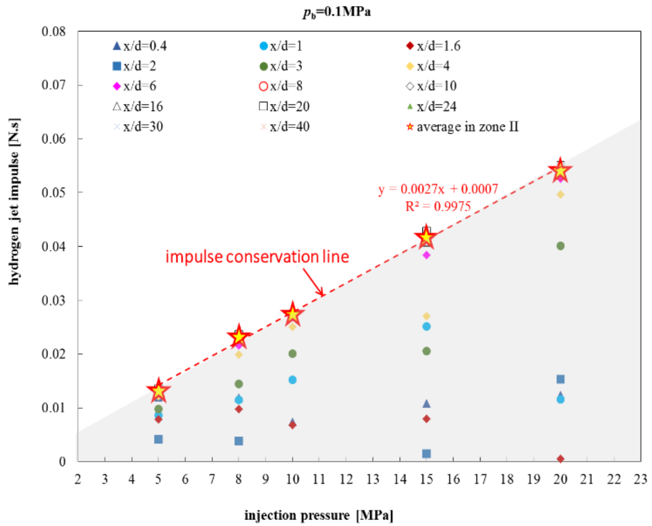
高压气体燃料射流冲动量具有两段式(2-stage)特点，近嘴端区域（near field）是动态区域(dynamic zone)，核心段区域（main jet region）是稳定区域(stable zone)，冲击动量不变（jet impulse is constant）。





$$H = 1.34 R_{nozzle} \sqrt{\frac{p_{in}}{p_b}} = 0.67 \sqrt{\frac{p_{in}}{p_b}} D_{nozzle}$$





高压气体射流冲击两阶段转折点：两阶段转折点的位置与马赫盘高度数值基本一致

The Mach disk height points are extremely close to the inflection points.

Publications

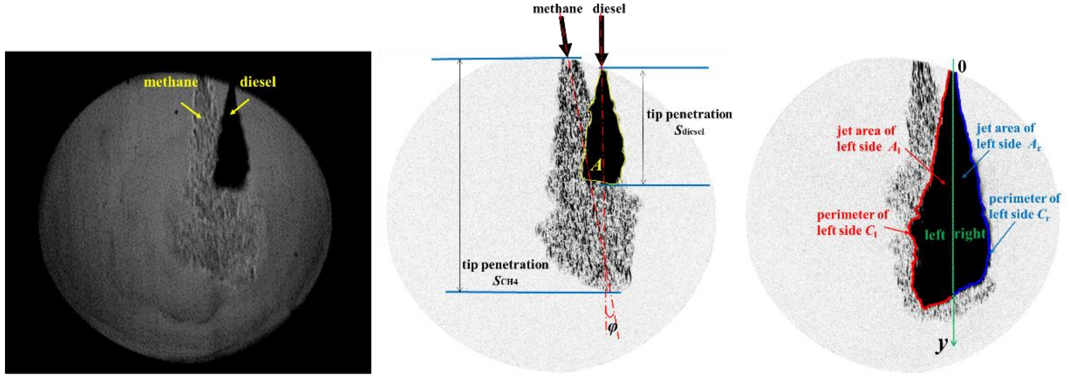
7. Yan Lei, Ao Zhang, Dingwu Zhou, et al. Experimental investigation of high-pressure hydrogen gas jet impingement characteristics of single-hole cylindrical injector. Energy Science & Engineering. 2023, 11:502-512.-396. (SCI)
8. 雷艳，李泳，李志杰，仇滔，常凯.甲烷高压射流动量特征，燃烧科学与技术，2021，27(2)：121-128.

二. 高压气体燃料直喷射流特性研究

Study on high-pressure gas fuel direct injection

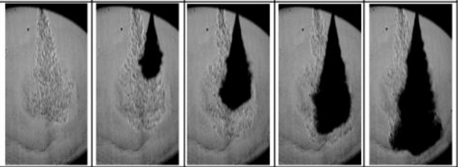
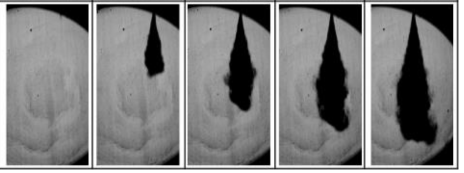
4.柴油-气体燃料双射流空间作用规律

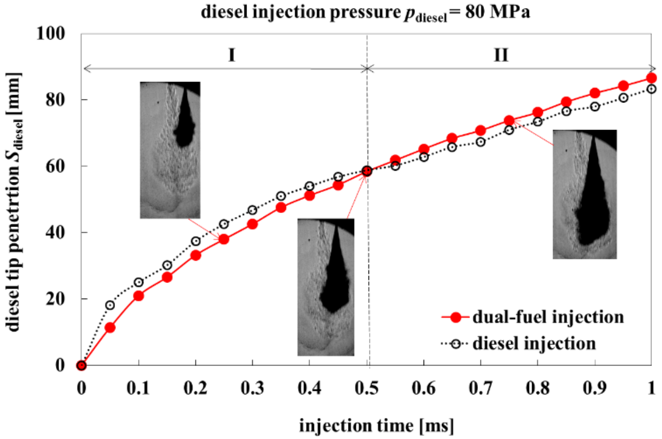
Diesel-gas fuel dual injection

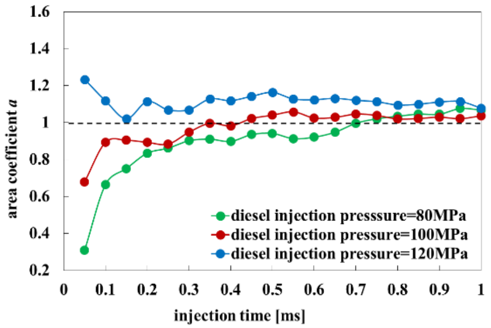


高压气体燃料射流影响柴油喷雾，早期双射流中柴油喷雾贯穿距、面积、周长均小于纯柴油喷雾；后期双射流中柴油喷雾贯穿距、面积、周长均增加，这是气体射流的作用结果。

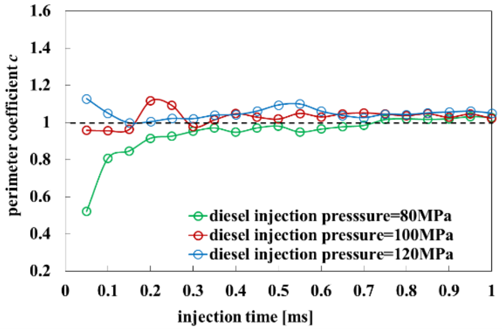
During the early stage I, the diesel tip penetration S_{diesel}, the diesel spray area A_{diesel} and the diesel spray perimeter C_{diesel} of the dual-fuel injection are smaller than those of the single diesel injection. During stage II, both the diesel and methane continue to penetrate forward and S_{diesel}, A_{diesel} and C_{diesel} of the dual-fuel injection become larger than those of the single diesel injection do.

Type \ Time	3 ms	3.25 ms	3.5 ms	3.75 ms	4.0 ms
Diesel-methane dual-fuel injection					
Diesel injection					





面积系数



周长系数

Publications

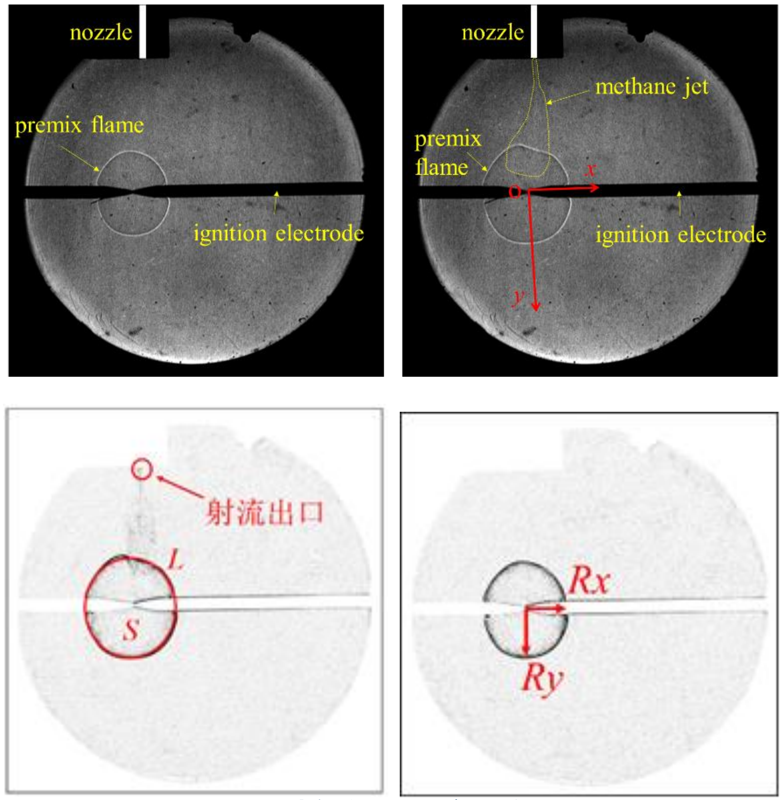
9. Yan Lei, Yue Wu, Tao Qiu, et al. Experimental Study of Dual-Fuel Diesel/Natural Gas High-Pressure Injection. ACS Omega 2023, 8, 519-528. (SCI)

目 录

- 一. 气体燃料缸内直喷技术
  Gas fuel direct injection technology
- 二. 高压气体燃料直喷射流特性研究
  Study on high-pressure gas fuel direct injection
- 三. 高压气体燃料射流燃烧特性研究
  Study on high-pressure gas fuel jet combustion
  - 1.气体燃料预混燃烧 Gas fuel premixed combustion
  - 2.气体燃料射流燃烧 Gas fuel jet combustion
- 四. 结论
  Conclusions

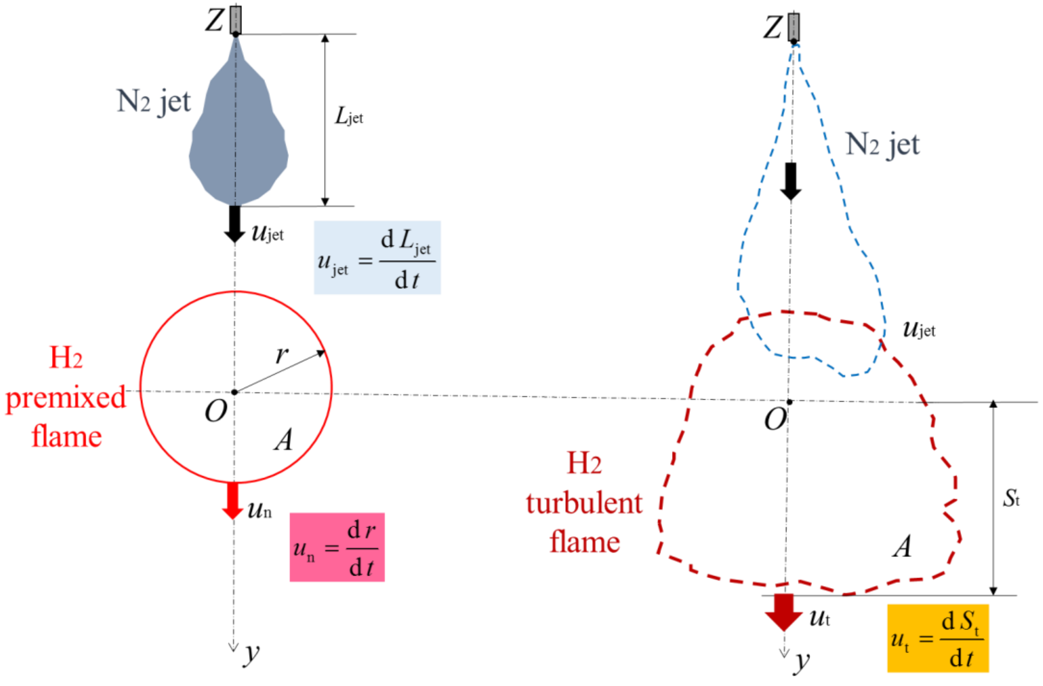
一.高压气体燃料射流燃烧特性研究

Study on high-pressure gas fuel jet combustion



火焰传播参数

Flame parameters



(a) Gas jet does not meet premixed flame　　(b) gas jet interacts with premixed flame

当量比计算

equivalence ratio

$$\phi = \frac{AF_{stoic} R_{air}}{R_{CH4}} \frac{p}{p_0 - p} = \frac{AF_{stoic} R_{air}}{R_{CH4}} \frac{1}{\dfrac{p_0 V}{p_{injection} A_{nozzle} t_{injection} \sqrt{k_{CH4} R_{CH4} T}} - 1}$$

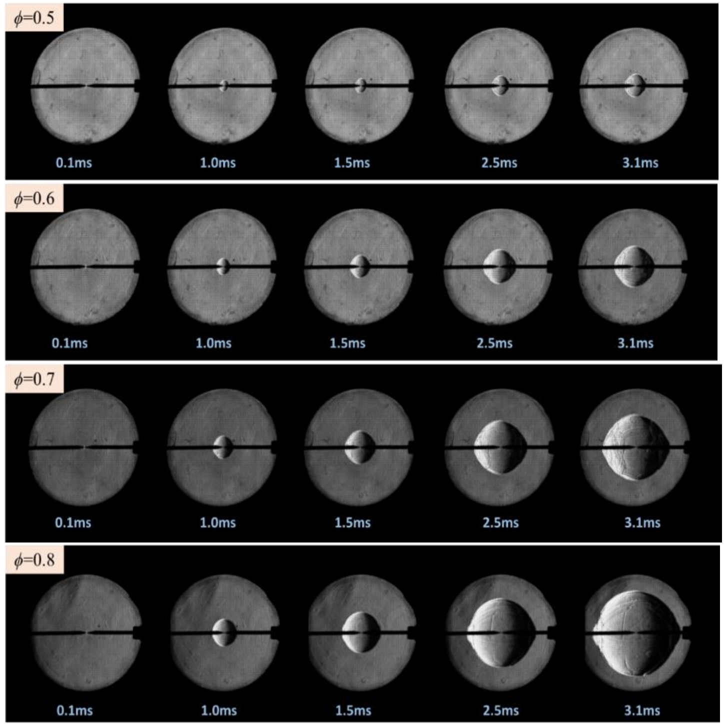
一.高压气体燃料射流燃烧特性研究

Study on high-pressure gas fuel jet combustion

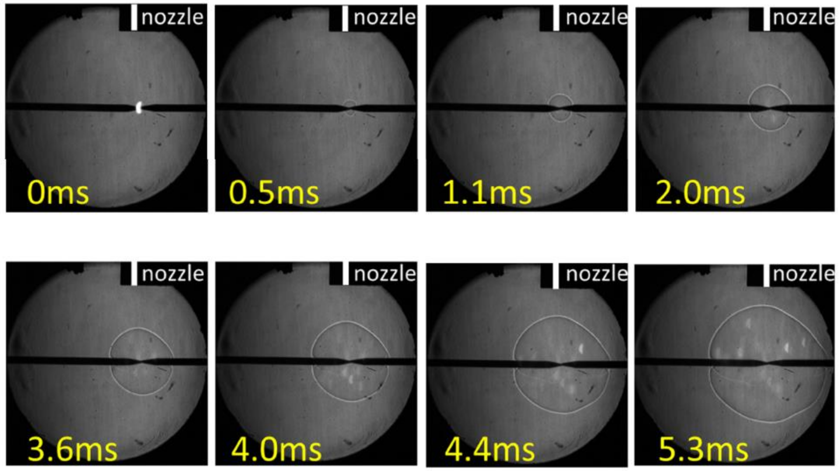
1.气体燃料预混燃烧

Gas fuel premixed combustion

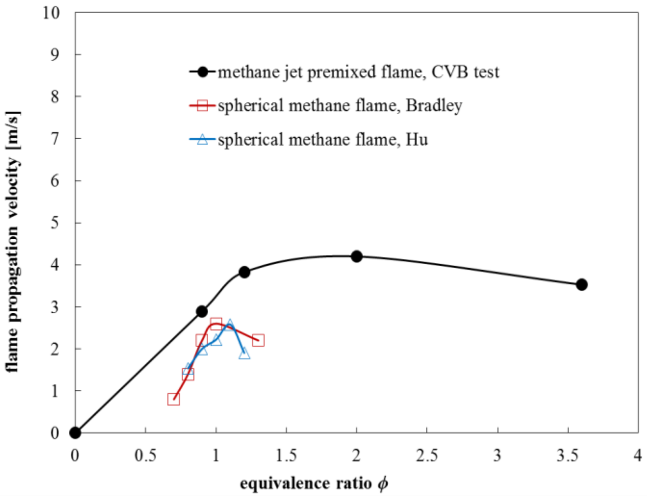
火焰成球形发展，传播速度稳定。Gas fuel premixed flame has a spherical shape, and propagates at a constant velocity.



氢气预混火焰 H2 premixed flame



甲烷预混火焰 CH4 premixed flame



Publications

10. Shenggang Guo, Yan Lei, XiaofengWang, et al. Experimental Research of High-Pressure Methane Pulse Jet and Premixed Ignition Combustion Performance of a Direct Injection Injector. Processes 2021, 9, 1977.(SCI)

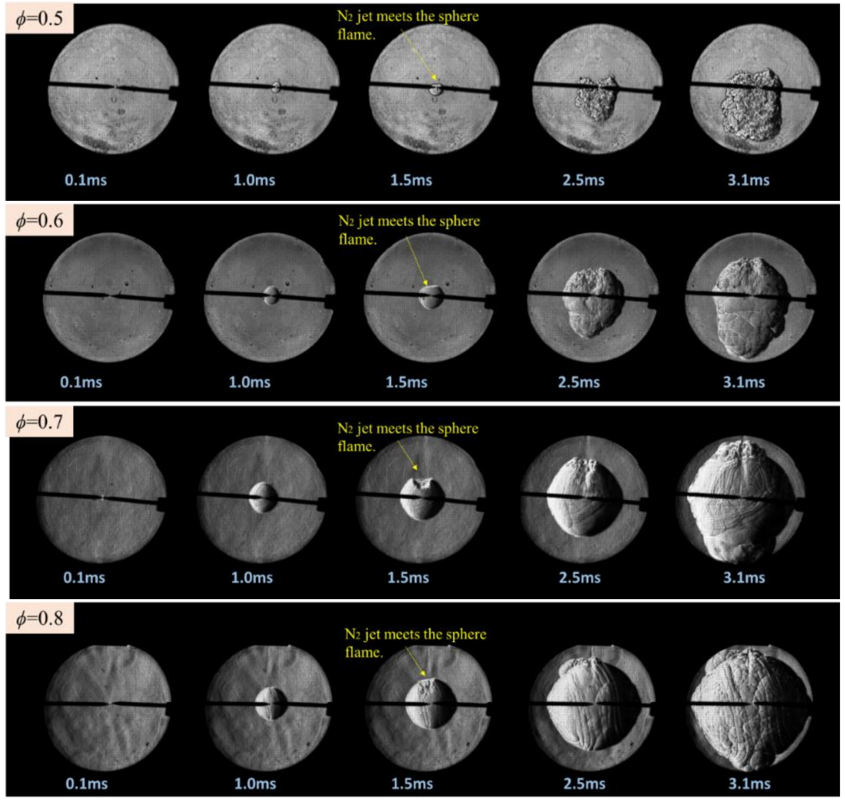
一.高压气体燃料射流燃烧特性研究

Study on high-pressure gas fuel jet combustion

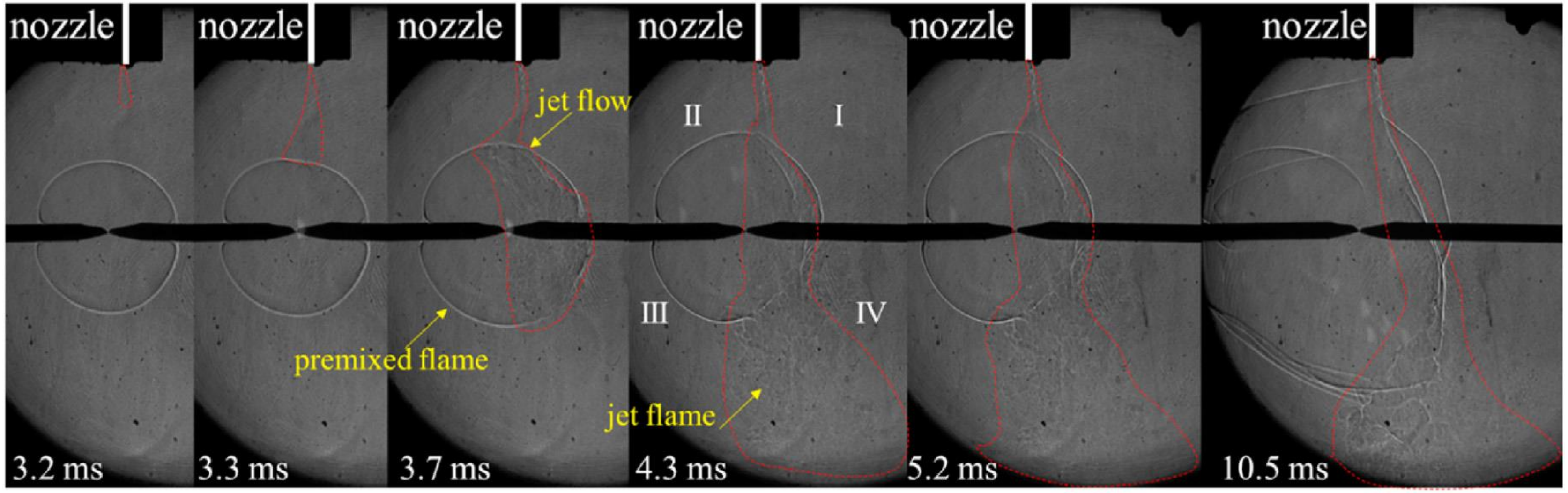
2.气体燃料射流燃烧

Gas fuel jet combustion

气体射流接触球形火焰后，火焰发生变形，并产生皱褶，火焰亮度增加，噪声更大，火焰发展为湍流燃烧火焰。After the gas jet meets the special flame, the flame deforms and cellular structure occurs. The flame releases large amounts of light and heat together with substantial noise. Turbulent flame occurs.



氢气射流火焰 H2 jet flame



甲烷射流火焰 CH4 jet flame

WEICHAI 潍柴

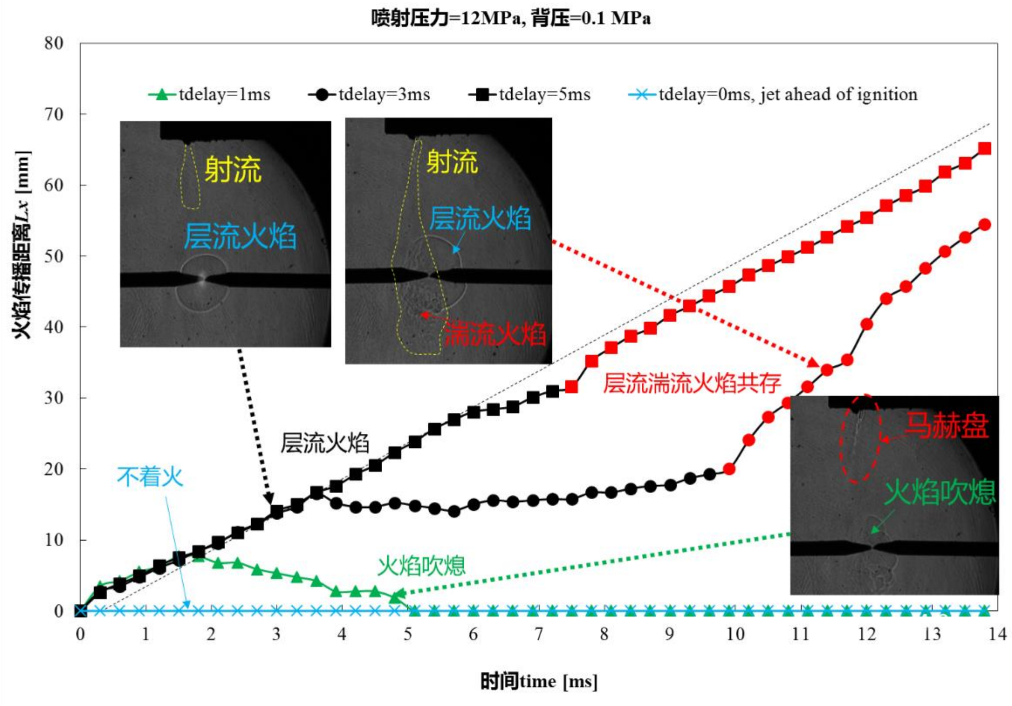
一.高压气体燃料射流燃烧特性研究

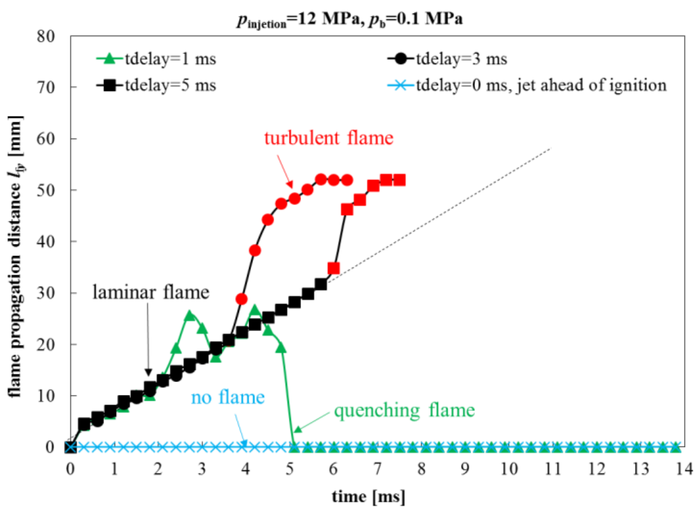
Study on high-pressure gas fuel jet combustion

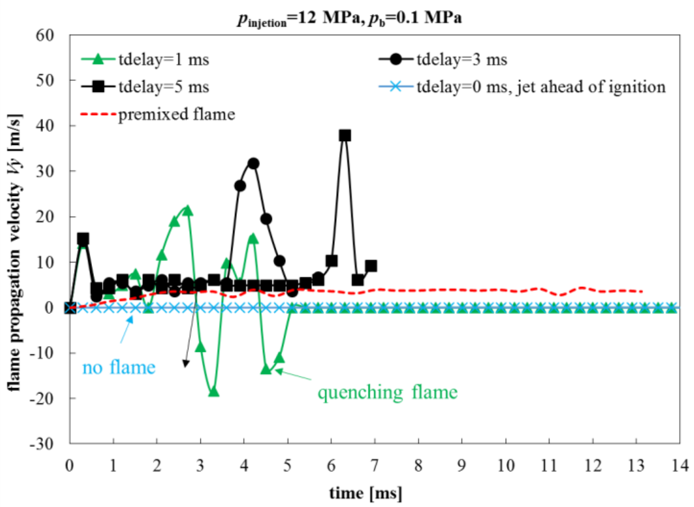
2.气体燃料射流燃烧

Gas fuel jet combustion

气体射流作用球形火焰有两种现象：火焰吹熄、火焰增强为湍流燃烧。 When the high pressure gas jet flow acts on the premixed flame, the spherical flame either quenches, or it expands to be turbulent flame.







沿气体射流方向火焰传播速度

Jet flame propagation velocity along the jet direction

Publications

11. Yan Lei, Yong Li, Tao Qiu, et al. Effects of high-pressure methane jet on premixed ignited flame in constant-volume bomb. Energy, 2021, 220: 119695. (SCI)
12. 雷艳，丁梦竹，仇滔,等. 高压甲烷射流对层流火焰作用的试验.内燃机学报,2022,39(02):113-118. (EI)

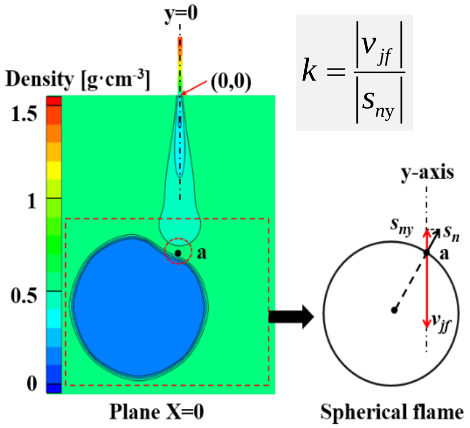
一.高压气体燃料射流燃烧特性研究

Study on high-pressure gas fuel jet combustion

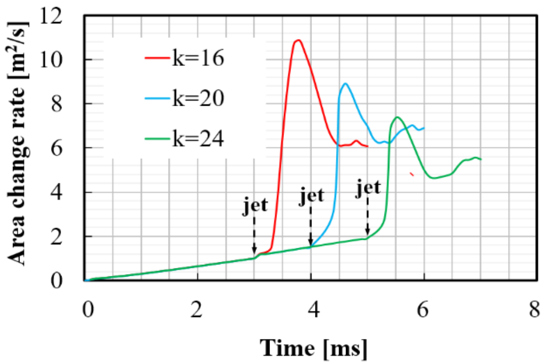
2.气体燃料射流燃烧

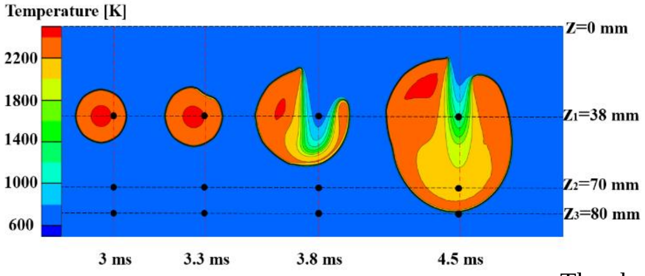
Gas fuel jet combustion

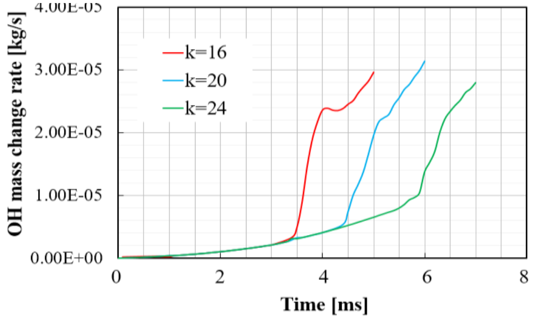
气体射流导致火焰局部吹熄，但是气体燃料射流引起当地当量比、涡旋及湍动能增加，促使形成适合着火条件并引燃未燃气体，加速燃烧，最终火焰发展为湍流燃烧。 **Turbulent combustion occurs in the turbulent combustion zone because of the vortex generated by the disturbance of the jet, which makes the gas in the unburned zone a suitable turbulent environment for combustion. .**



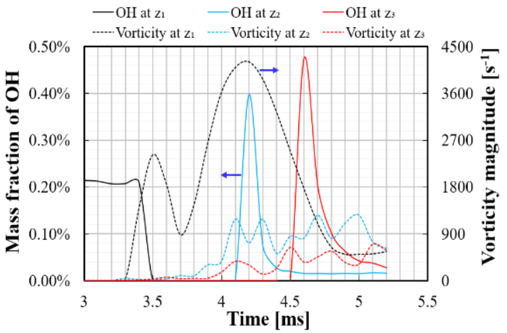
$$k = \frac{|v_{jf}|}{|s_{ny}|}$$

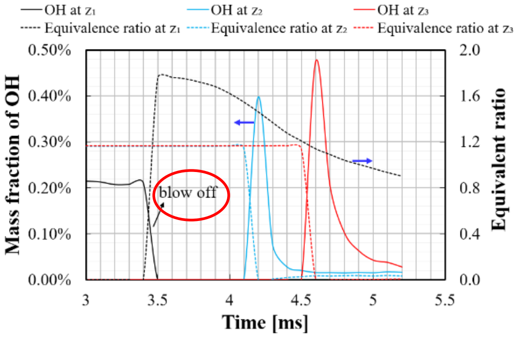


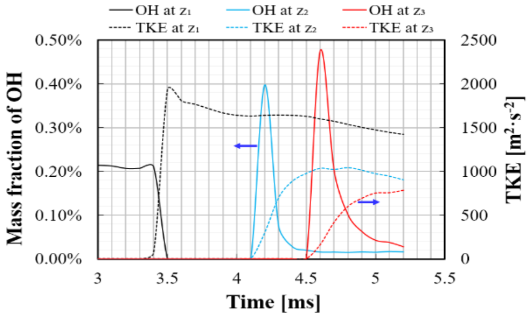




The change rate of OH in the flow field representing the intensity of combustion increases abruptly by 4–9 times







气体射流导致火焰局部吹熄。

The turbulent energy induced by the jet is excessively large, and the heat is insufficient to support the formation of a high-speed stable flame, resulting in flame failure

Publications

13. Tao Qiu, Yuwan Deng, Yan Lei , et al. Numerical simulation of the influence of high-pressure methane jet on the premixed ignition flame of constant volume bomb. Fuel 321 (2022) 124003. (SCI)

14. 仇滔,邓玉婉,雷艳,等.预燃火焰引燃高压甲烷射流的数值模拟.内燃机学报,2022,40(06):513-518. (EI)

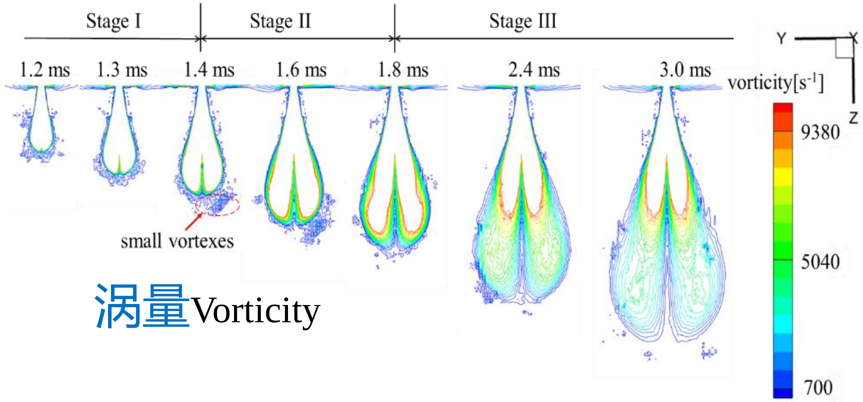
一.高压气体燃料射流燃烧特性研究

Study on high-pressure gas fuel jet combustion

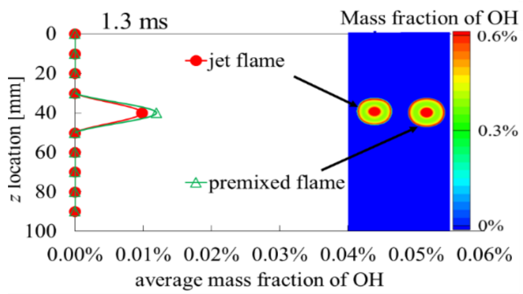
2.气体燃料射流燃烧

Gas fuel jet combustion

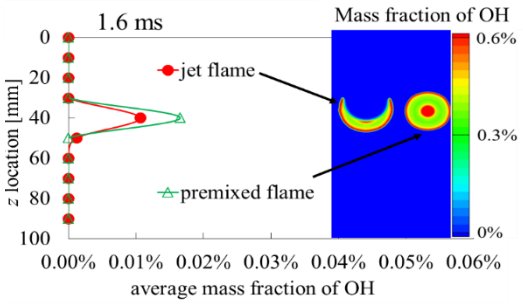
气体射流由预混火焰引燃形成湍流燃烧，涡量、OH基陡增，火焰传播速度为预混火焰的3倍，射流火焰传播速度的增加主要是受射流涡量的影响。 **Gas fuel jet combustion is turbulent, both vorticity and OH mass fraction sharply increase. The jet flame velocity is 3 times of the premixed flame speed, and it is mainly affected by the jet vorticity.**



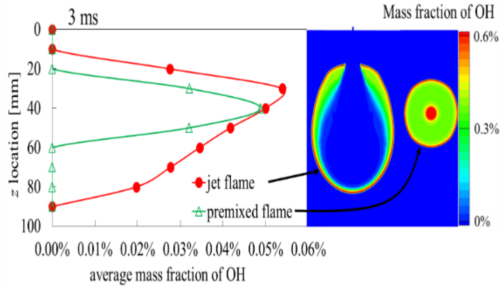
涡量Vorticity



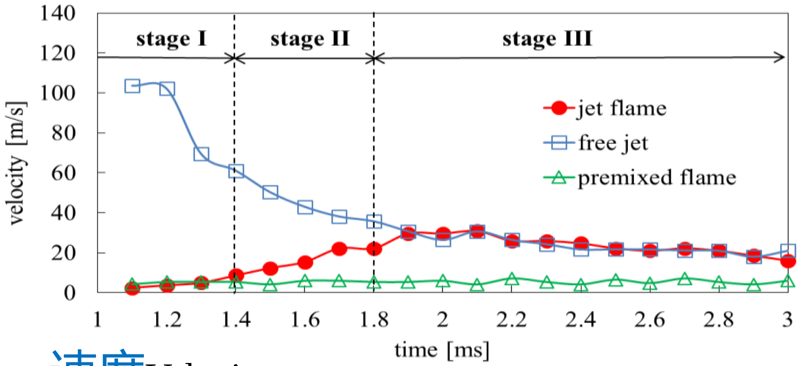
Stage I



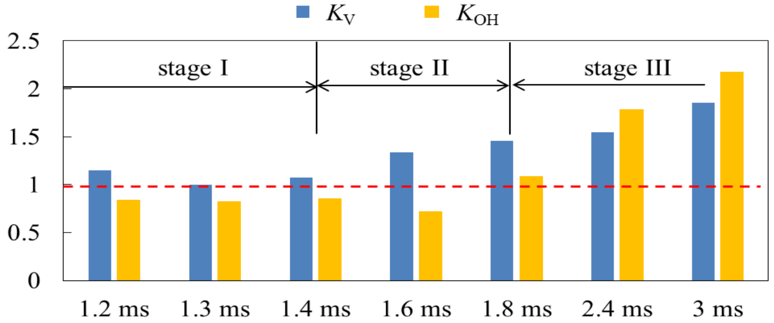
Stage II



Stage III



速度Velocity



K_v, K_{OH} represent the comparison of the vorticity and the OH mass fraction respectively between the jet flame and the premixed flame

- During stage I, $K_v > 1 > K_{OH}$, the voriticity is notable due to the methane jet.
- During stage II, K_v increases while K_v declines, the high-pressure methane jet plays a major role.
- During stage III, both K_{OH} exceeds K_v, the combustion plays a chief part while the high-pressure gas jet causes less effects in late stage III of the flame propagation process.

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目 录

4.结论Conclusions

- 高压气体燃料缸内直喷为音速射流，出现激波。

Gas fuel direct injection is sonic jet with shock waves.

- 激波引起近嘴端射流速度增加，冲击动量下降并波动，导致射流具有两段式特性：近嘴端（波动段）和远嘴端（稳定段）。

Shock waves result in gas jet velocity increasing and impingent momentum fluctuation. The gas jet has two-stage behavior: stage I near field is dynamic and stage II stable field is stable.

- 射流可吹熄已燃火焰；着火点位于射流波动段，火焰稳定性差，易熄火。

Gas jet may cause flame quench. The flame close to the jet fluctuation zone has worse stability.

- 高压气体射流对火焰主要起拉伸作用，火焰拉伸率、涡量增加，导致湍流火焰传播速度骤增。

High-pressure gas jet causes stretch effect on the premixed flame, and the jet flame stretch rate and vorticity increase, which results in the flame propagation velocity sharply rises.

谢谢

Thanks

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