Primary and secondary particulate matter formation and evolution in the whole process with direct injection gasoline engines

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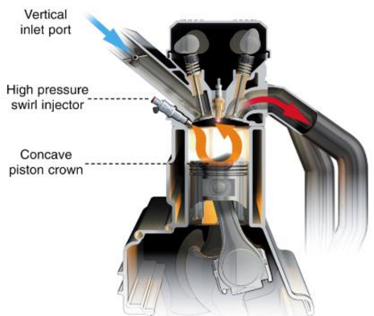
Cambridge Particle Meeting 2019
28th June, 2019

Outline

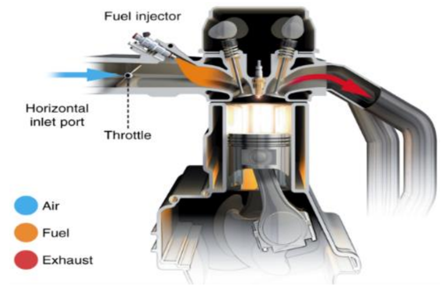
- **Motivation and background**
- **Methodology**
- **Results and discussion**
- **Conclusions**

Research background

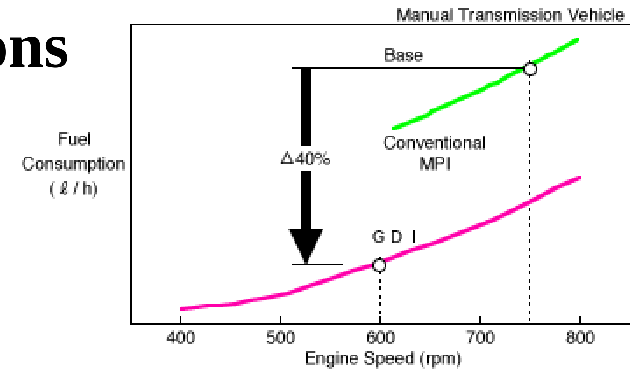
- **GDI vehicle has more particle emissions**



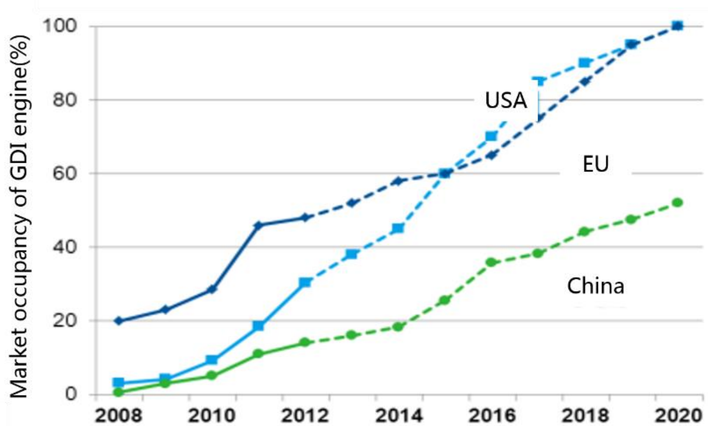
GDI engine



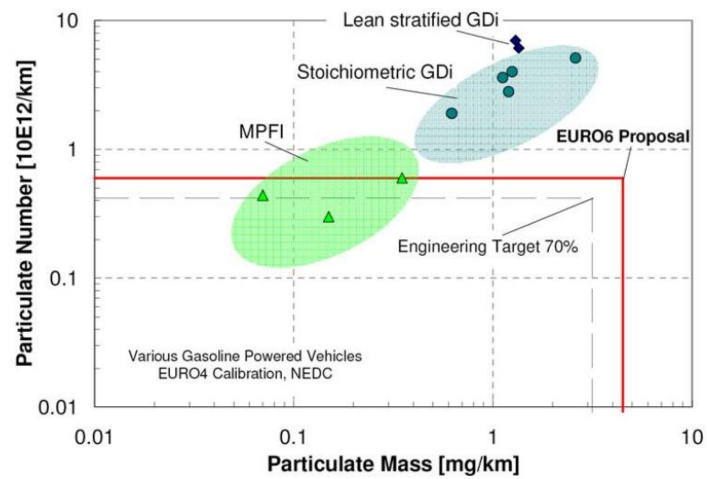
PFI engine



GDI fuel consumption ~saving 40%



GDI engine increase tendency



GDI particle emission is a challenge

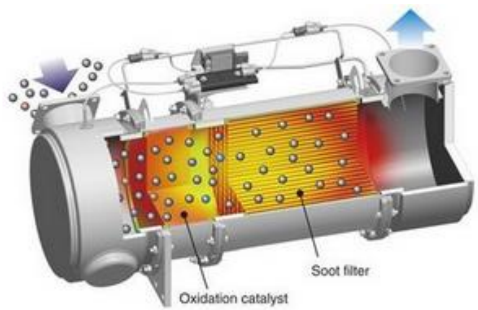
1) GDI engines, have high efficiency, are widely used in gasoline vehicles

2) However, primary particle and VOCs from GDI engines are one of the main sources for fog and haze

Research background

- Recent research on vehicle particle emissions

In-cylinder soot



Particles in Exhaust system

Tailpipe particle emission

Atmospheric particles

Issues：

- In-cylinder soot、particles in exhaust systems、particles in tailpipes and atmospheric particles are researched separately.
- Lack of research integrating “In-cylinder—exhaust gas—atmosphere”
- Lack of research on the mechanism and theory of soot and particle mode evolution

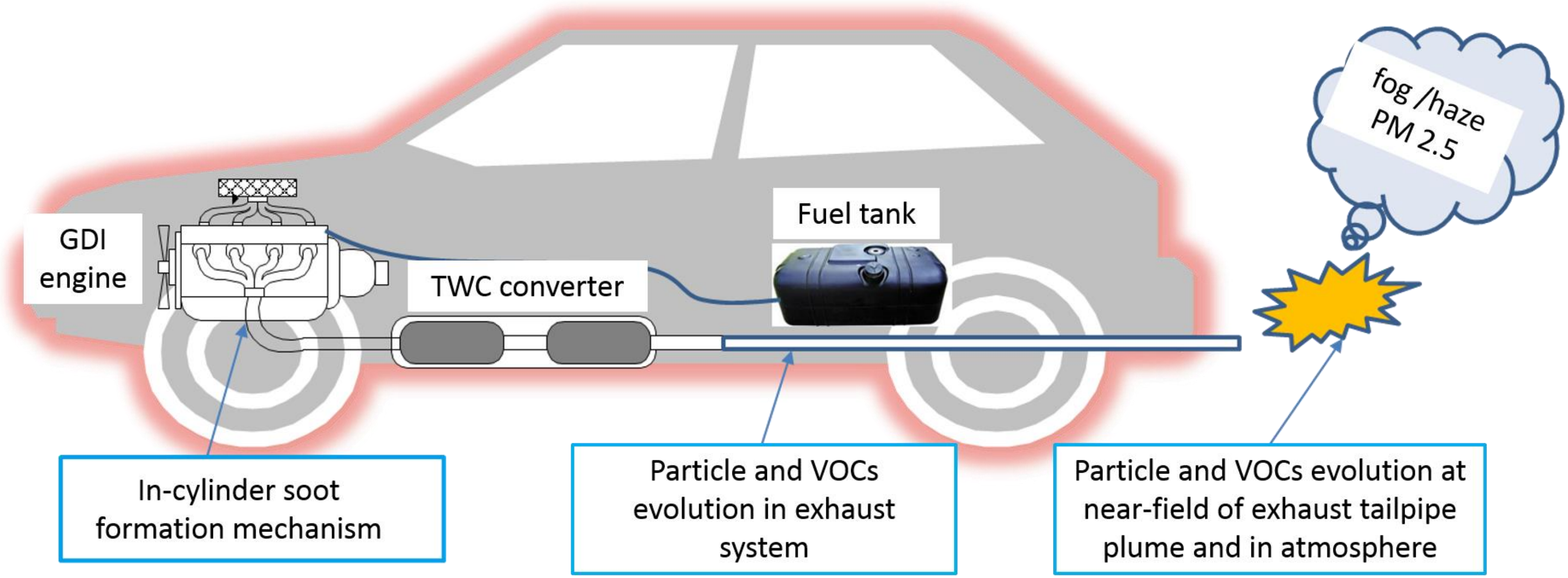
Issues of PM Evolution

1） In-cylinder soot formation, origin of particles and influence factors

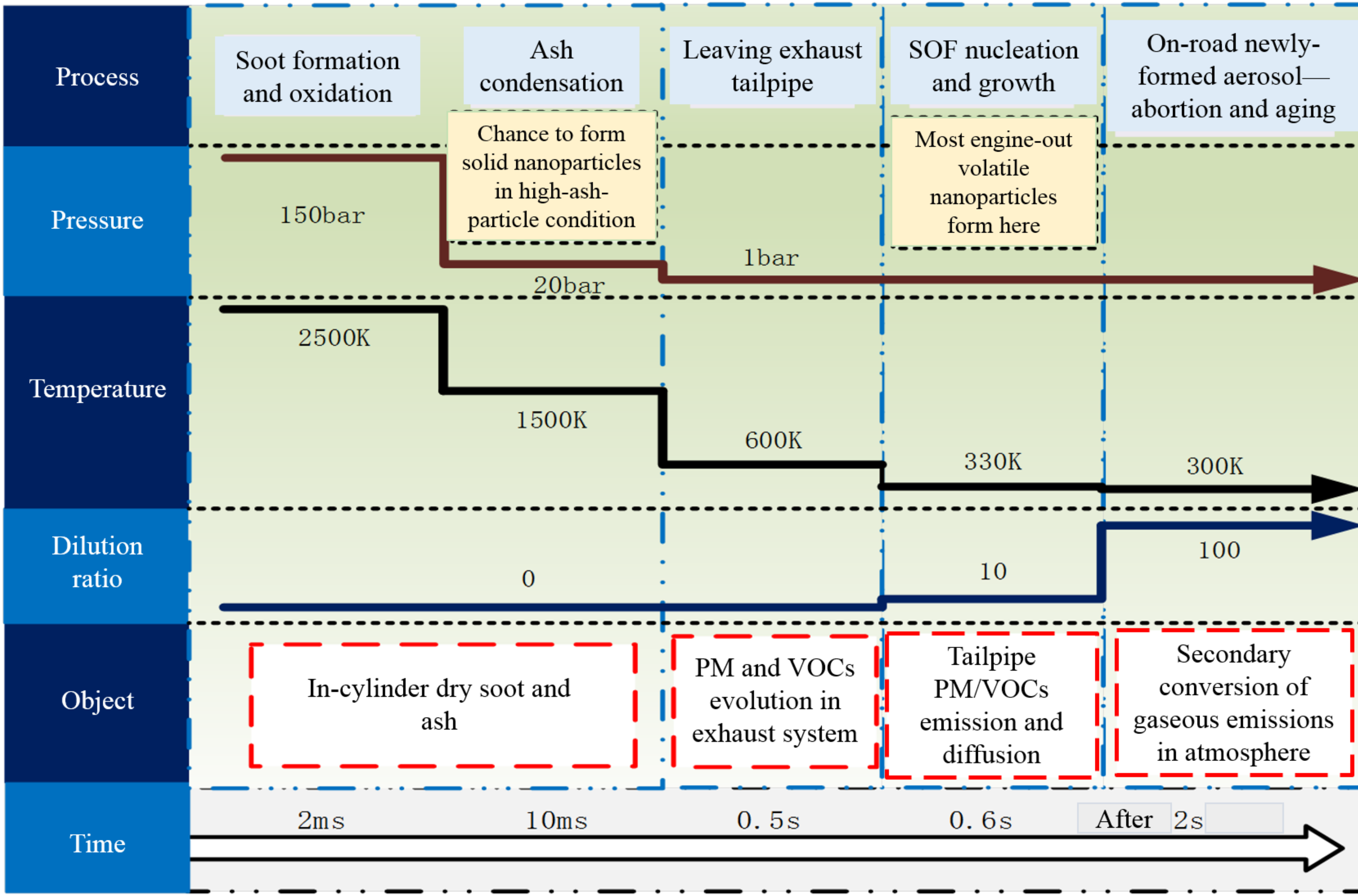
2） Particle evolution in exhaust systems and key influence factors

3） Particle and gaseous emissions evolution mechanism at near-field of exhaust tailpipe plume

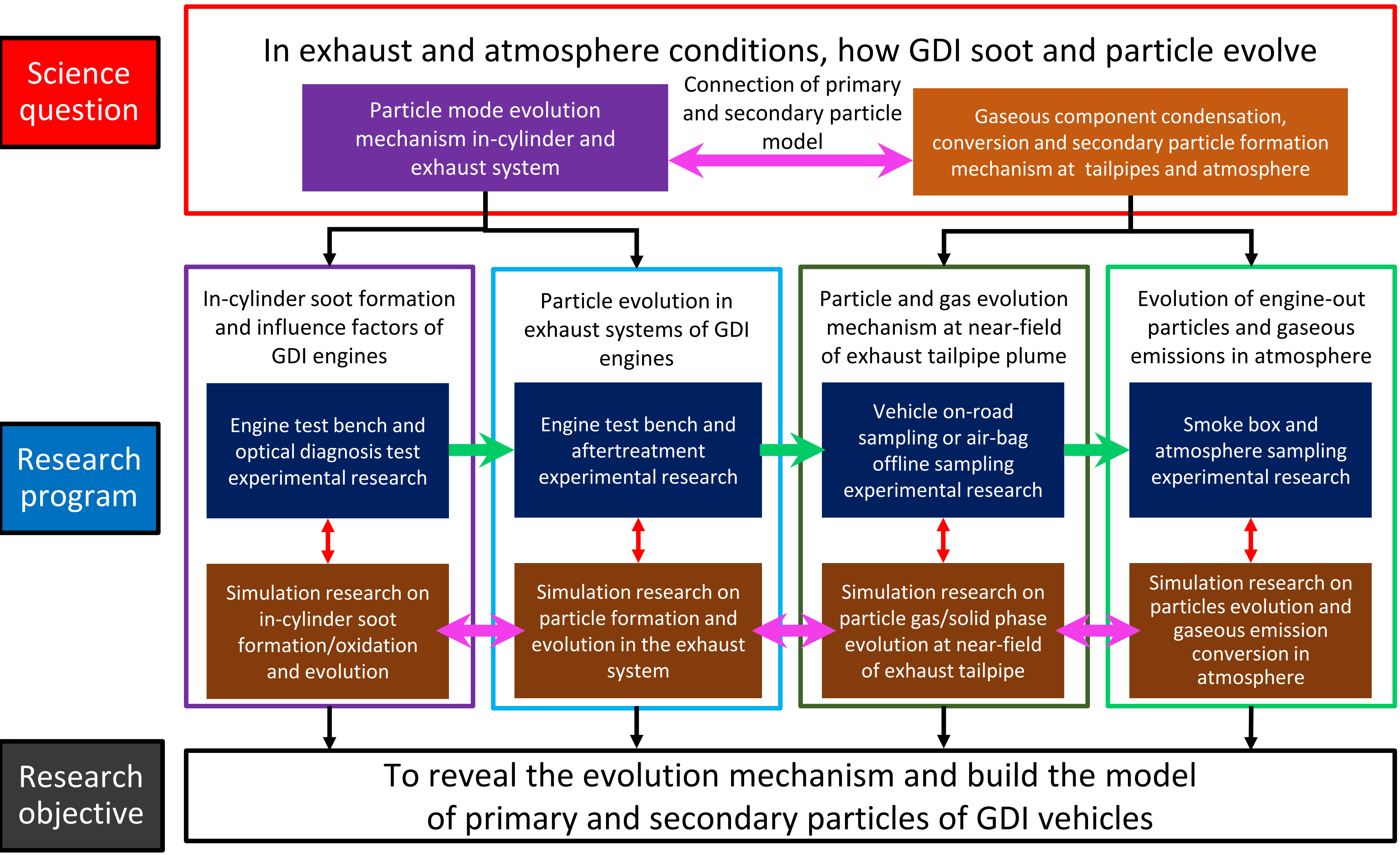
4） Evolution of particles and engine-out gaseous emissions in atmosphere



Physical evolution conditions

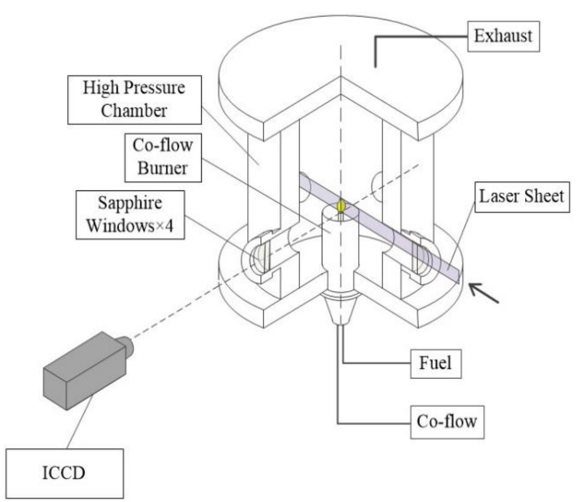


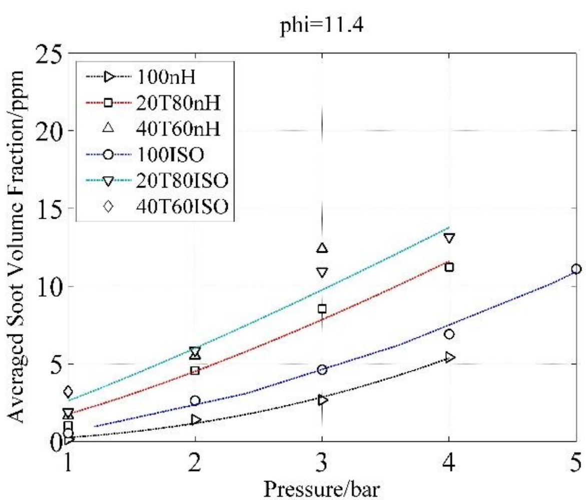
Rresearch Technology pathways

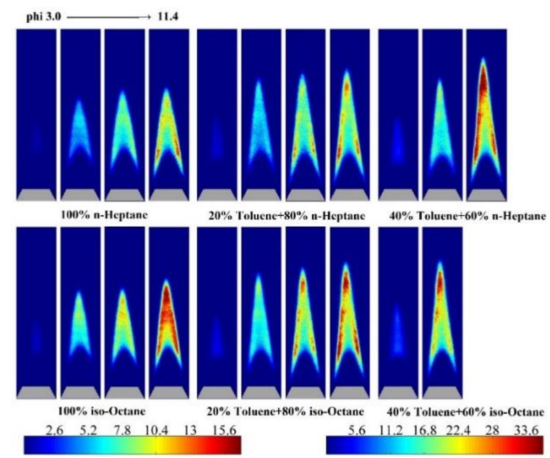


PAHs formation mechanism at high pressure

- As back pressure increases, flame width becomes narrow and the lower boundary of soot area moves to the outlet of fuel, PAH-LIF area shrinks
- As back pressure increases, tendency to form PAHs increases. The bigger molecule of PAHs, the more influences from back pressure increase.
- At atmosphere pressure, in fuel-rich region, soot locates in the flame tip; with the increase of back pressure, soot also generates in flame wings
- The influence of backpressure on soot is similar to that on PAHs. The formation of PAHs is highly related to the formation of soot.
- Average soot volume fraction(f_v) has a relation with back pressure: $f_v = Cp^n$, the range of the exponent is 1.07-2.20, depending on fuel components and equivalence ratios



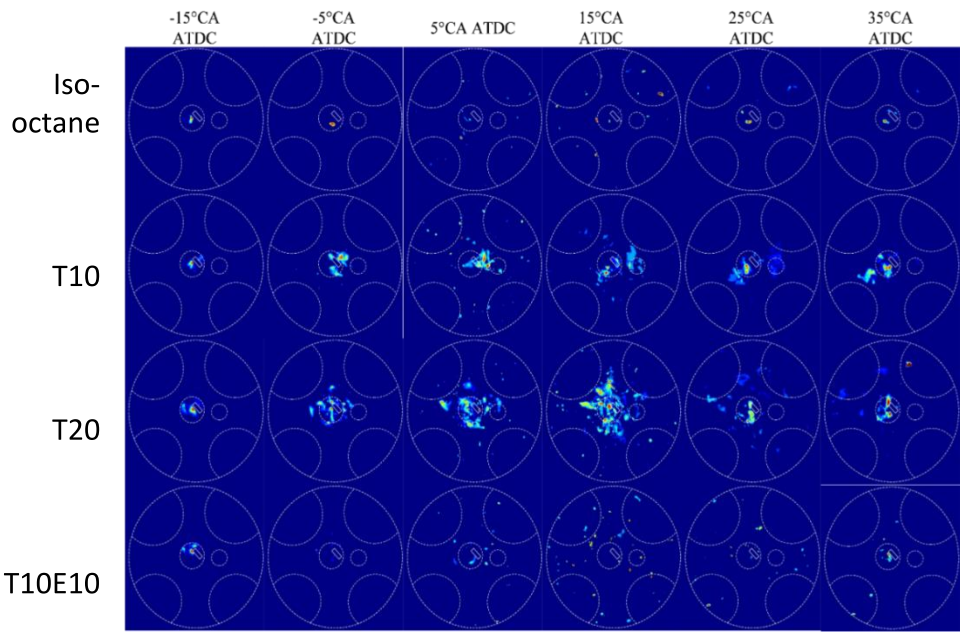


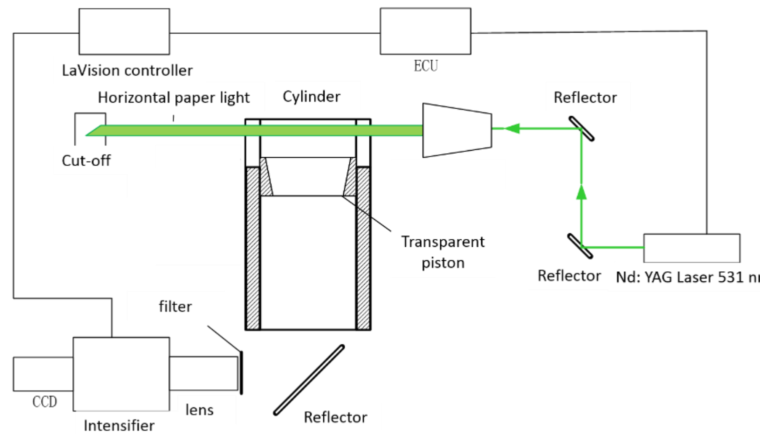


Average SVF of flame vs back pressure (Φ=11.4)   Flame soot volume fraction distribution at 4bar

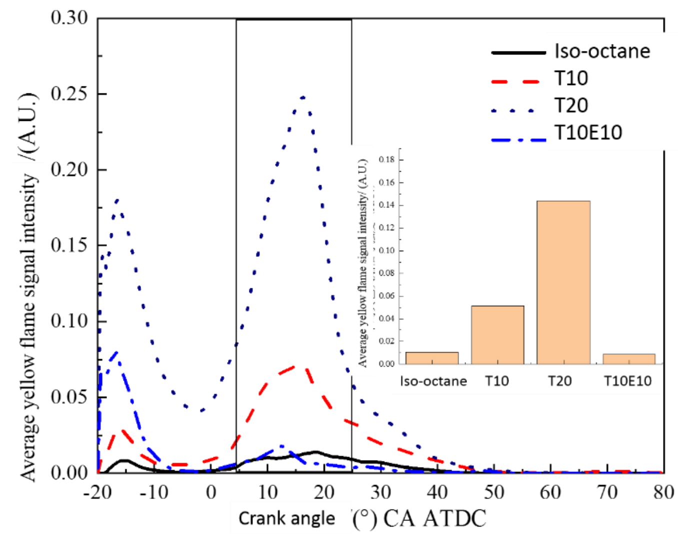
Factors influence the formation of soot

- Flame distribution at stoichiometry





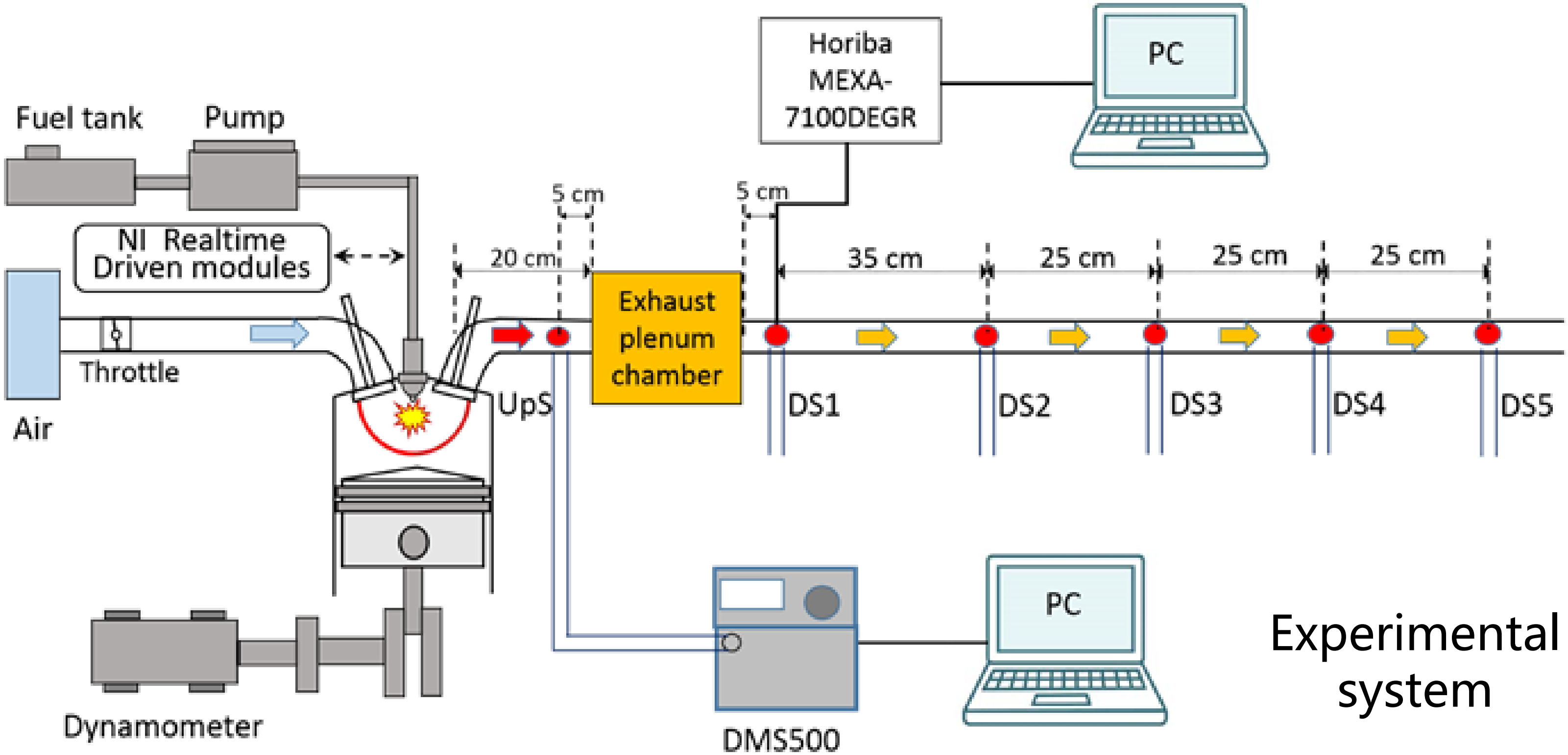
- At stoichiometry, in-cylinder soot comes from spark events, late combustion of droplet from spark plug and injector and local fuel-rich regions;
- Toluene increases soot, while ethanol decreases it;
- Soot forming in spark events are one of the origin of engine-out soot emissions.



Yellow flame intensity and average of yellow flame intensity from 5°CA ATDC to 25°CA ATDC

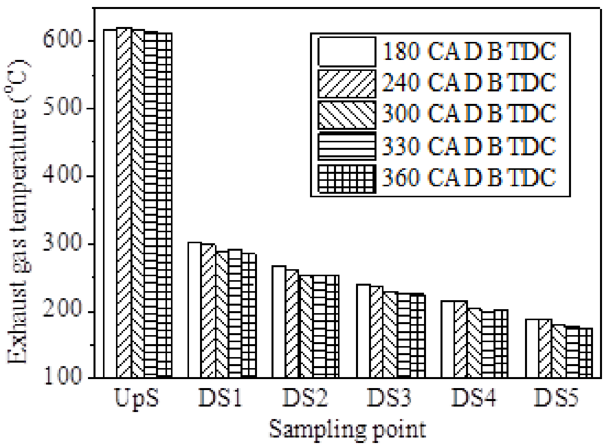
Particle evolution inside exhaust system

Gas temperature changes dramatically in the exhaust pipe, where coagulation, condensation may occurs, resulting in particle components, morphology, mode variations.

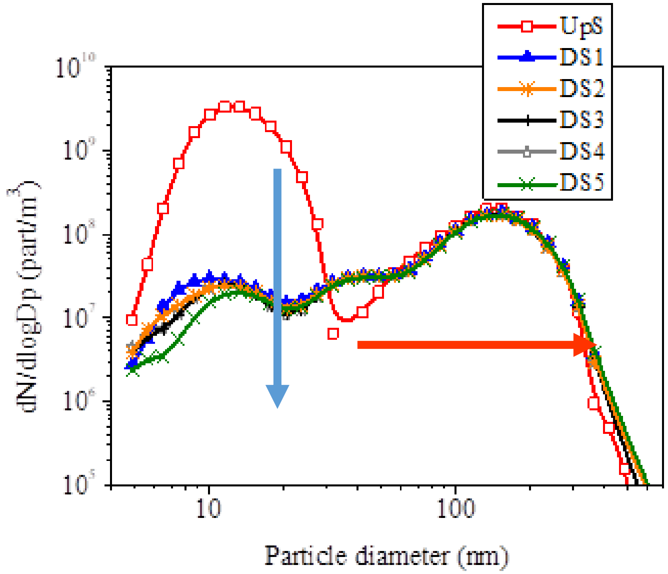


Experimental system

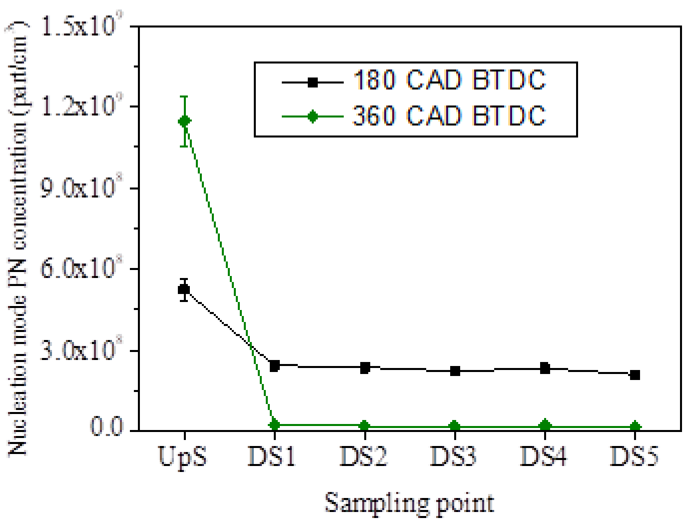
Particle evolution inside exhaust system



Temperatures of sample positions



SOI 360°CA BTDC



Nucleation mode particle number variation

Findings：

- Coagulation results in large number reduction of nucleation mode particles
- With the flow of exhaust gas, accumulation mode PN decreases by 7-10%, nucleation mode PN decreases by 50-98%.
- Variation relies on SOI

Particle evolution inside exhaust system

Research method:

- Analyzed soot evolution in-cylinder or in tailpipes by TEM graph analysis.
- Developed two Matlab codes to analyze particle morphology based on Refs （Yehliu, 2011; Toth, 2013). Method2 has faster calculation speed (increase 50%) and more data (increase 100%).

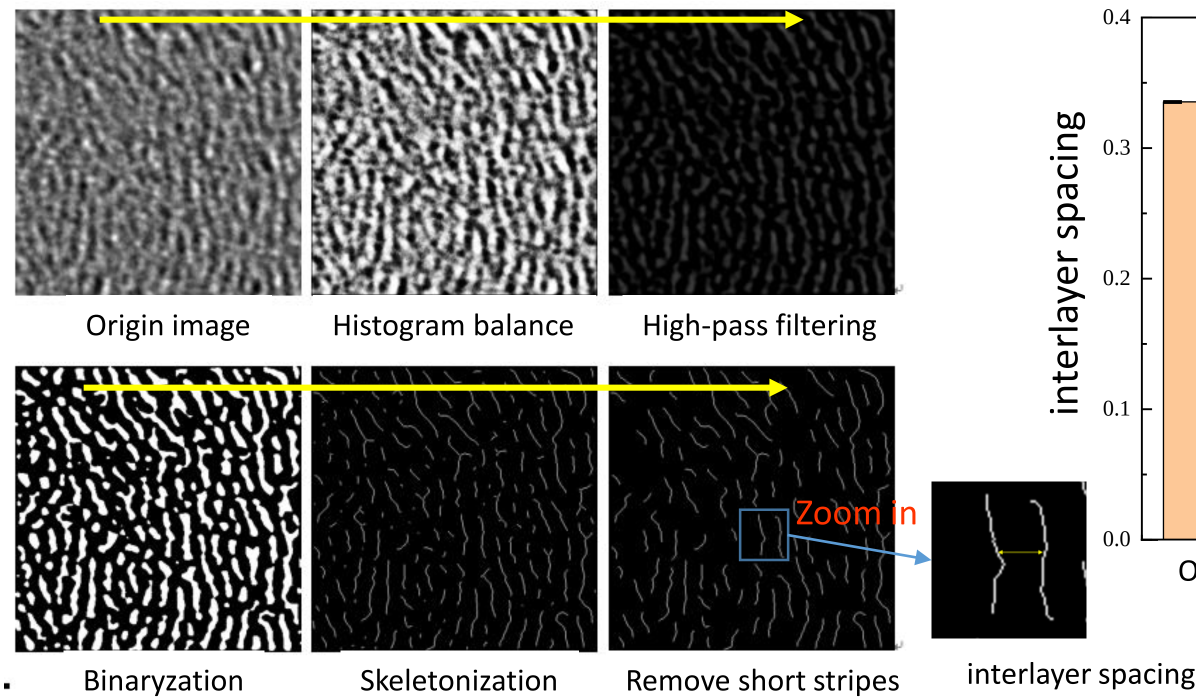
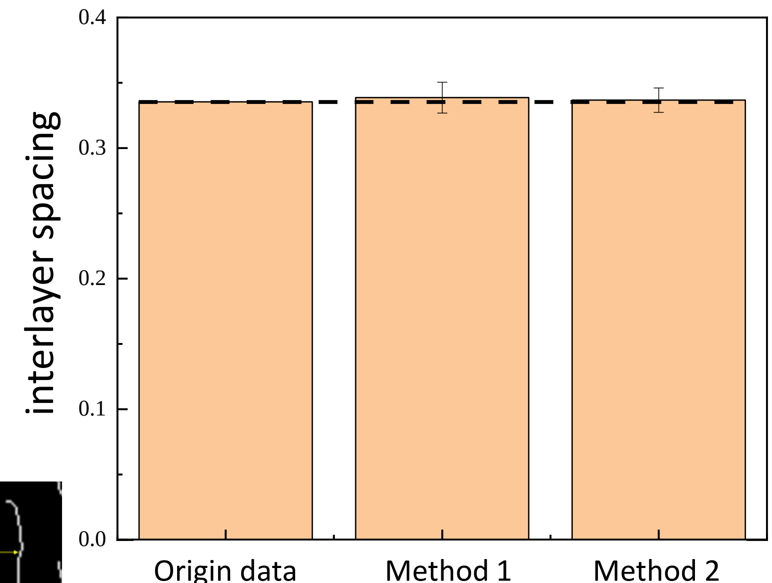


Image processing



The results obtained by the two methods are the same as origin

interlayer spacing: average distance between adjacent stripes, reflecting particle maturity and oxidation activity

Particle evolution inside exhaust system

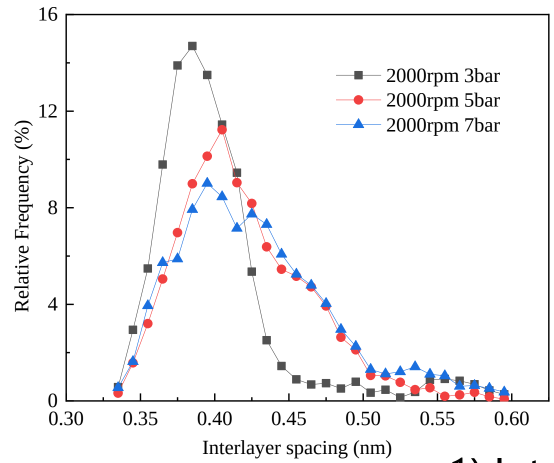
Findings:

1) interlayer spacing of particles increase as load increases

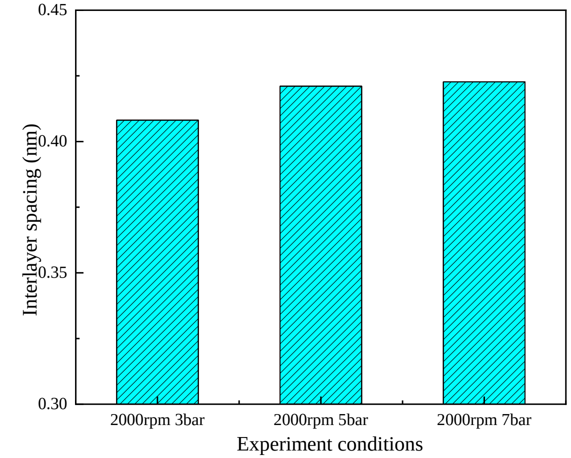
- At high load, combustion temperature is high and oxidation effect is more obvious, leading to interlayer spacing increase

2) The average interlayer spacing doesn' t show clear trend of change with the increase of engine speed.

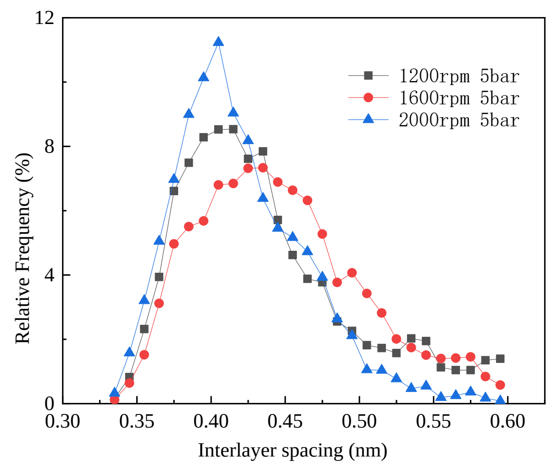
interlayer spacing distribution

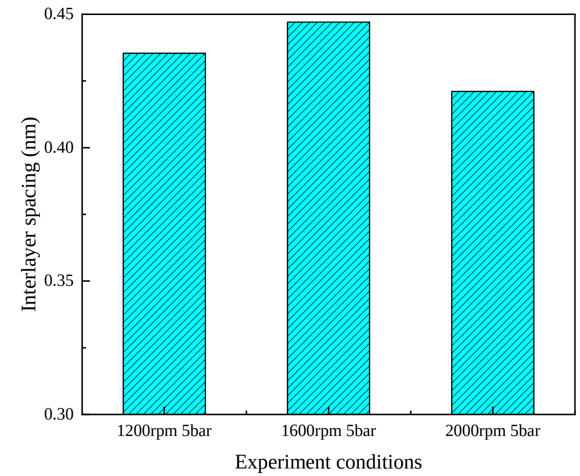


Average value of interlayer spacing



1) Interlayer spacing vs. load



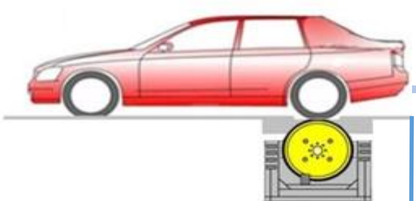


2) Interlayer spacing vs. speed

Measurement at near-field of tailpipe plume

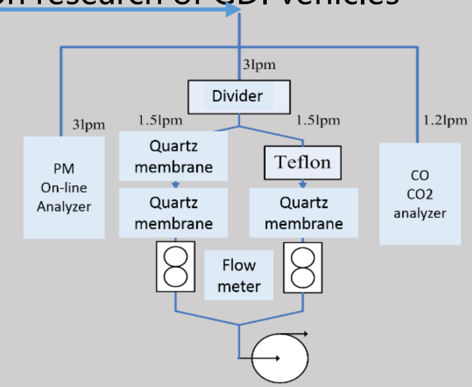
At tailpipe exit, exhaust smoke plume is formed; primary particle characters change with air flow; secondary particles are formed from primary particles and gases

- Integrated experiments of full-process of particle evolution



Sample along plume

Outlet of tailpipe and near-field pollution evolution research of GDI vehicles



Dilution system

Primary particle

Smoke box

Replace

PAM Reactor

Secondary particle

Evolution of particles and engine-out gaseous emissions in atmosphere

Instrument	Application
Ptr-ToF-MS	Yield way to estimate SOA(impact of S/IVOC)
O_3	OH exposed quantity，OH day
NOx	Effects of NOx on SOA
SMPS	Spectrum
CPMA	Density
AMS	Chemical component
CO_2	Calibrate AMS m/z 44
CO	OH consumption
相态	SOA(solid/semi-liquid/liquid)

Spectrum + Density → Total mass

Measurement at near-field of tailpipe plume

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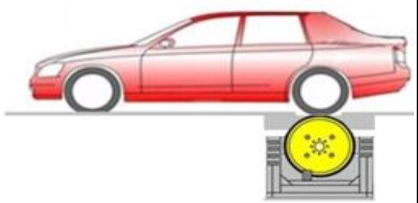
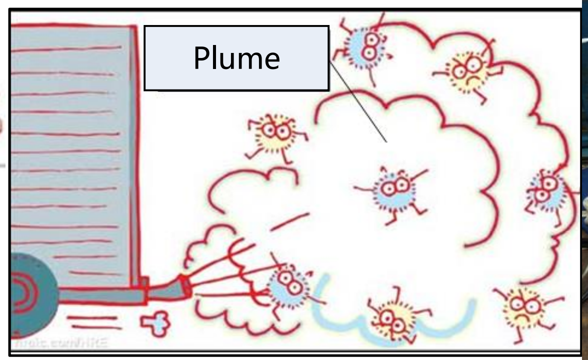
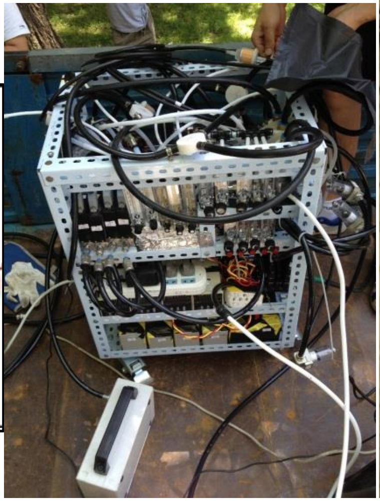
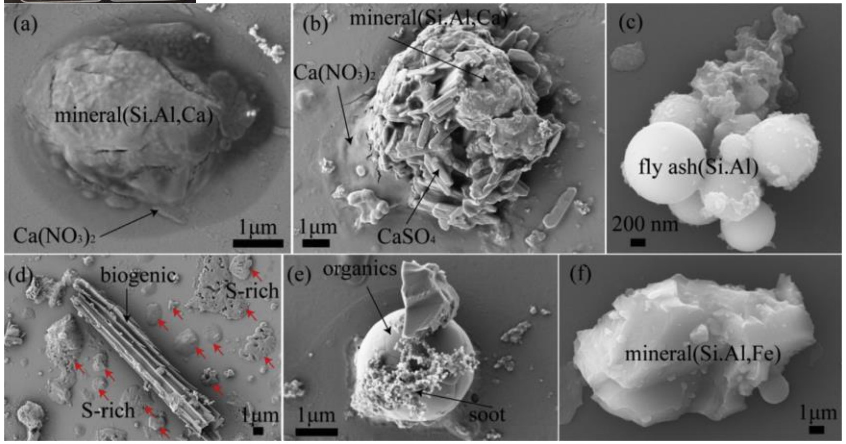
- Exhaust tailpipe near-field measurement





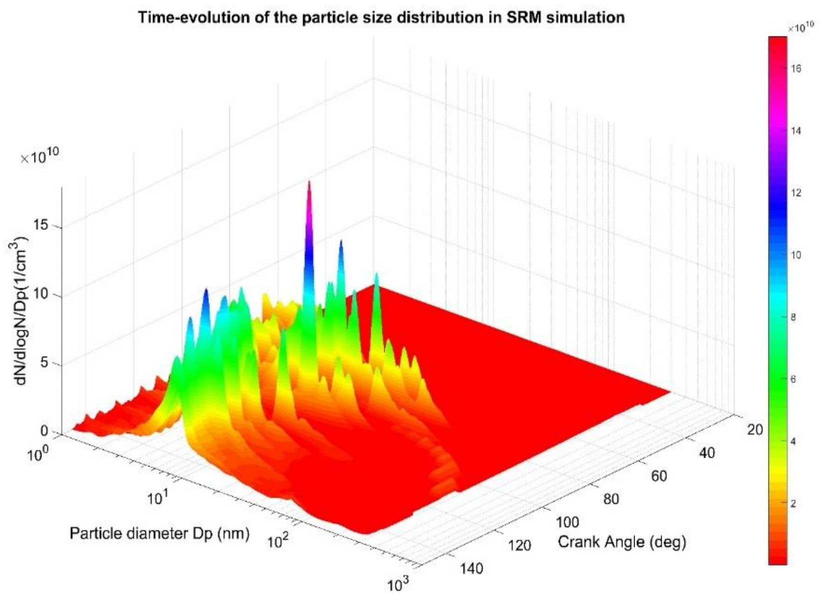


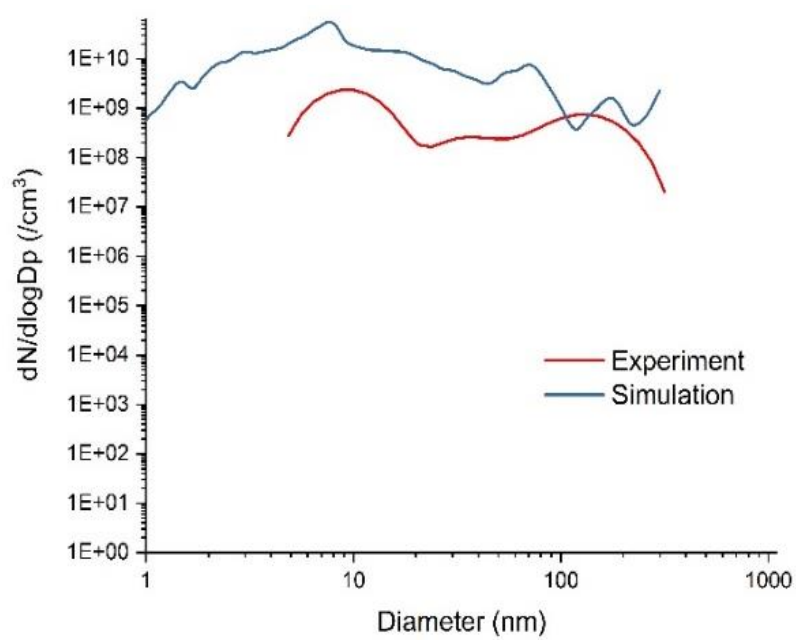


Simulation of particles evolution

In-cylinder particle formation model from Cambridge based on Monte-Carlo method

- Based on multi-component chemical kinetics, simulate soot formation, number, size and mass distribution; simulate GDI engine performance and emissions according to fuel components and engine conditions
- **The simulation results match the experimental measurement data very will on particle number, size and mass distributions**





Simulation of particles evolution and gaseous components

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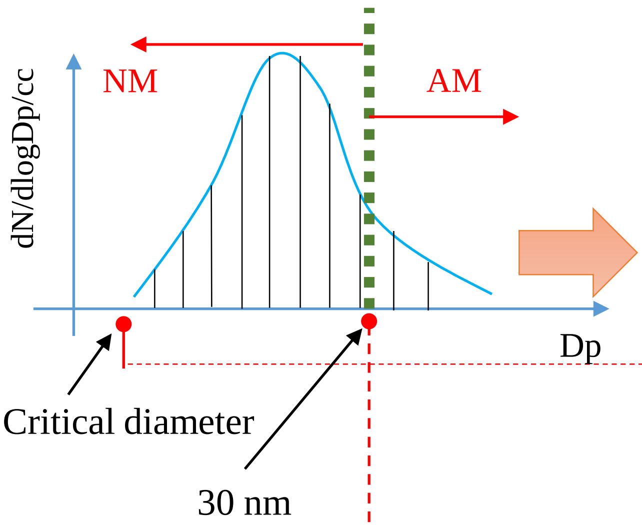
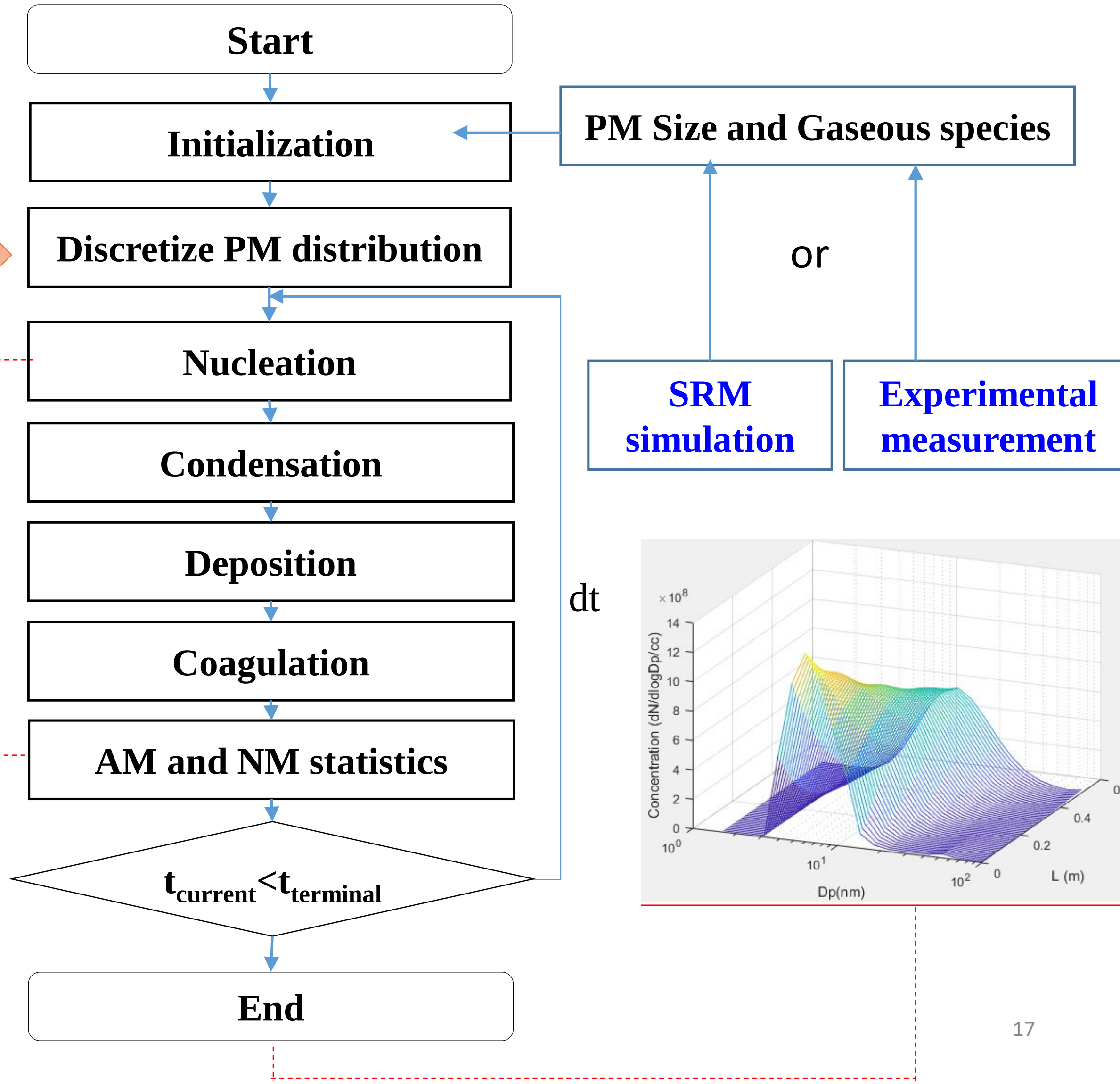
- Develop in-house software for the simulation





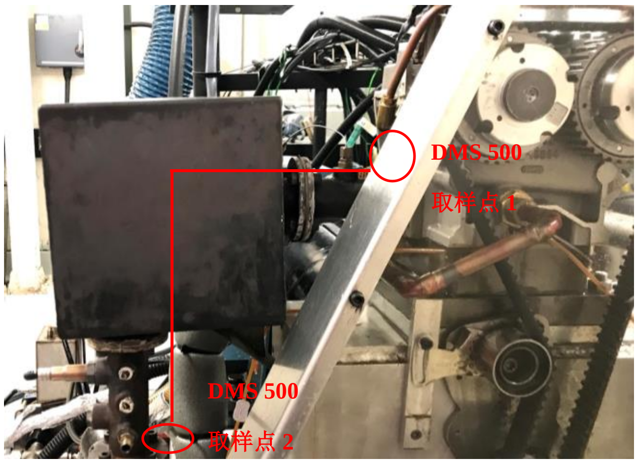
Calculation method:

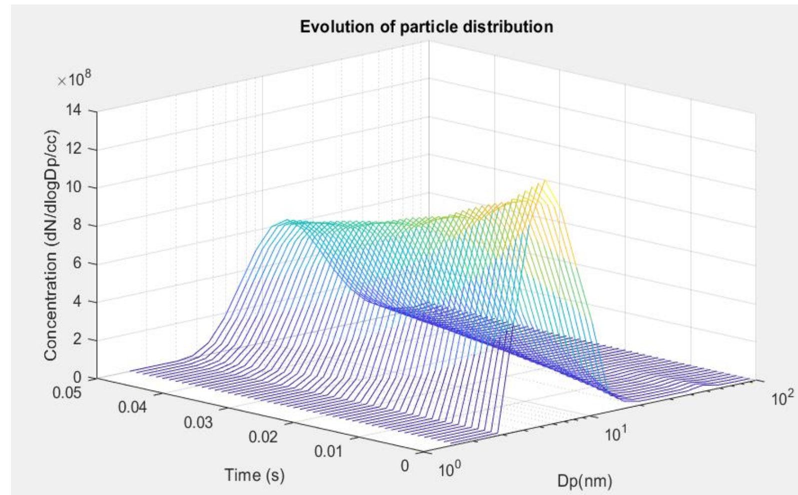
- Divide particles into *n* segments

Gaseous HC components: alkane(C4-C8), n-Butanol, benzene and toluene.

Simulation of particles evolution

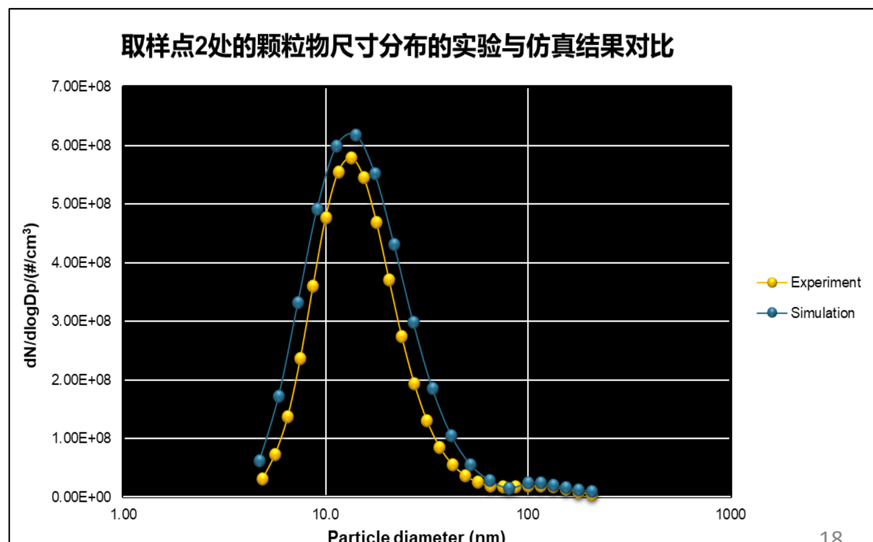
Comparison of simulation and experimental results





粒径分布随时间的发展

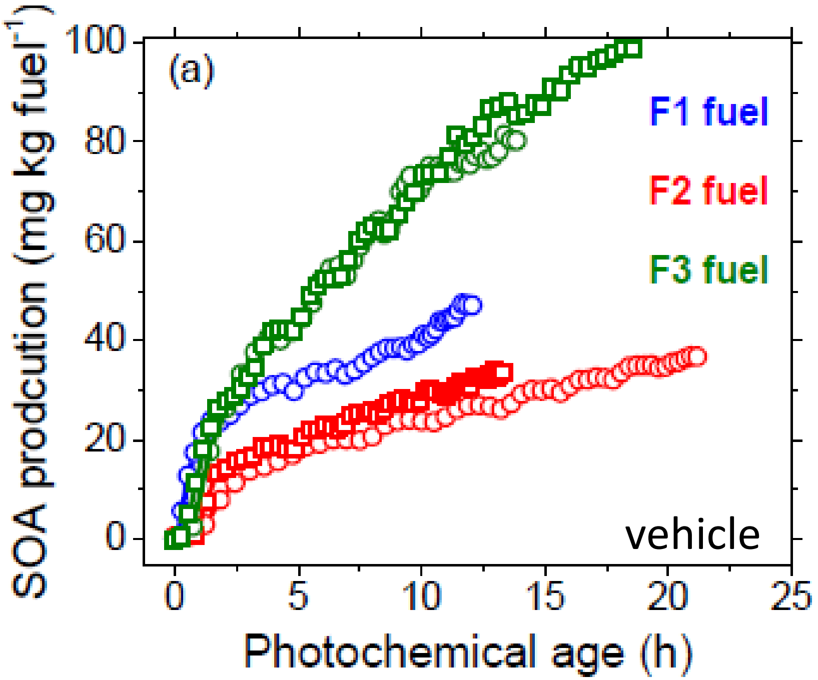
Take testing data from P1 as simulation input, and testing data from P2 are compared with simulation output.

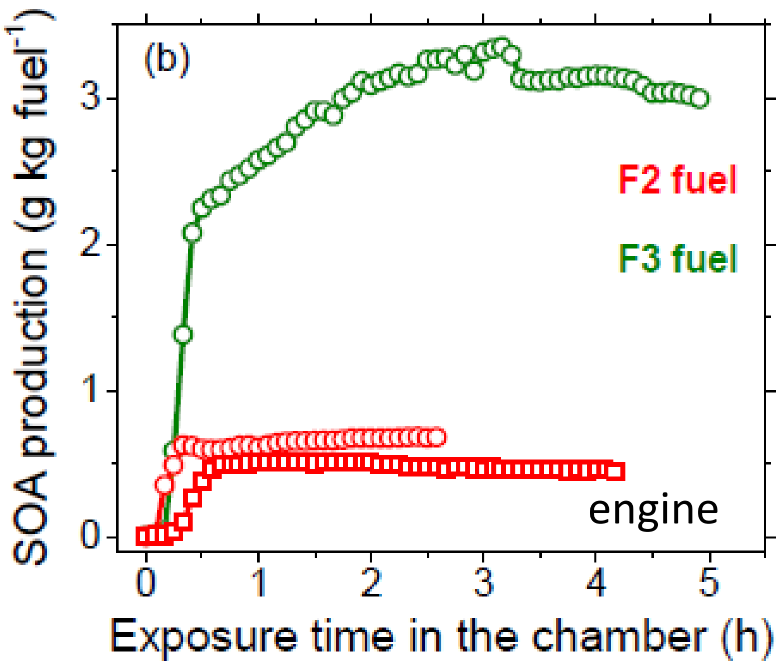


Findings：

- As time passes, （exhaust gas flow downstream），particle average size increases, particle number decrease
- The simulation results match well with the experimental data

Formation potential of secondary particles





- The higher aromatics concentration is for the fuel, the higher potential of secondary particle formation

Properties	F1	F2	F3
Aromatics (%v/v)	29.8	28.5	36.7
Olefins(%v/v)	4.1	18.8	16.4

Summary and Main Conclutions

- The formation characteristics and precursors of soot for gasoline surrogates are obtained in a high-pressure flame, and the influence of pressure on precursors and soot formation is researched.
- The effects of GDI engine combustion parameters on the formation of soot in the cylinder are investigated in detail.
- The influence of fuel properties on secondary particles was analyzed. It was found that aromatics had an important influence on secondary particles, and IVOC was considered to also have an effect on secondary particle formation.
- A research method for IVOC was introduced, and it was found that IVOC is the components that contributes the most to secondary particles.
- Taking advantage of international cooperation, the Monte-Carlo method was successfully introduced to establish the particle generation and evolution model of GDI engine and verified by experiment data.
- The theory of diesel particulate agglomeration was successfully used to establish the evolution model of gasoline engine particulate matter.

Publications (1)

1) *Y. Li, H. Guo, X. Ma, Y. Qi, Z. Wang, H. Xu and J. Wang, Morphology analysis on multi-jet flash-boiling sprays under wide ambient pressures, *Fuel*, 2018, vol. 211, pp:38-47.
2) *H. Guo, X. Ma, Y. Li, S. Liang, Z. Wang, H. Xu, J. Wang, Effect of flash boiling on microscopic and macroscopic spray characteristics in optical GDI engine, *Fuel*, 190 (2017) 79-89.
3) *H. Guo, H. Ding, Y. Li, X. Ma, Z. Wang, H. Xu, J. Wang, Comparison of spray collapses at elevated ambient pressure and flash boiling conditions using multi-hole gasoline direct injector, *Fuel*, 199 (2017) 125-134.
4) *Z. Wang, H. Guo, C. Wang, H. Xu, Y. Li, Microscopic level study on the spray impingement process and characteristics, *Applied Energy*, 197 (2017) 114-123.
5) *Wang, Ziman; Li, Yanfei; Guo, Hengjie; Wang, Chongming; Xu, Hongming (2018): Microscopic and macroscopic characterization of spray impingement under flash boiling conditions with the application of split injection strategy. In *Fuel* 212, pp. 315–325.
6) *Wang B, Jiang Y, Hutchins P, et al. Numerical analysis of deposit effect on nozzle flow and spray characteristics of GDI injectors[J]. *Applied Energy*, 2017.
7) Gu F, Hu M, Zheng J, et al. Research Progress on Particulate Organonitrates[J]. *Progress in Chemistry*, 2017, 29(9): 962-969.
8) Hu W, Hu M, Hu W W, et al. Seasonal variations in high time-resolved chemical compositions, sources, and evolution of atmospheric submicron aerosols in the megacity Beijing[J]. *Atmospheric Chemistry and Physics*, 2017, 17(16): 9979-10000.

Publications (2)

9. Peng J, Hu M, Du Z, et al. Gasoline aromatics: a critical determinant of urban secondary organic aerosol formation[J]. *Atmospheric Chemistry and Physics*, 2017, 17(17): 10743.
10. *Badawy T, Attar MA, Xu H, Ghafourian A. Assessment of gasoline direct injector fouling effects on fuel injection, engine performance and emissions. *Applied Energy* 2018;220:351–74.
11. Badawy T, Attar MA, Hutchins P, Xu H, Krueger Venus J, Cracknell R. Investigation of injector coking effects on spray characteristic and engine performance in gasoline direct injection engines. *Applied Energy* 2018;220:375–94.
12. Wang Y, Hu M, Guo S, et al. The secondary formation of organosulfates under interactions between biogenic emissions and anthropogenic pollutants in summer in Beijing[J]. *Atmospheric Chemistry and Physics*, 2018, 18(14): 10693-10713.
13. Tan T, Hu M, Li M, et al. New insight into PM 2.5 pollution patterns in Beijing based on one-year measurement of chemical compositions[J]. *Science of the Total Environment*, 2018, 621: 734-743.
14. Du Z, Hu M, Peng J, et al. Potential of secondary aerosol formation from Chinese gasoline engine exhaust[J]. *Journal of Environmental Sciences*, 2018, 66: 348-357.
15. Du Z, Hu M, Peng J, et al. Comparison of primary aerosol emission and secondary aerosol formation from gasoline direct injection and port fuel injection vehicles[J]. *Atmospheric Chemistry and Physics*, 2018, 18(12): 9011-9023.
16. Shang D, Hu M, Zheng J, et al. Particle number size distribution and new particle formation under the influence of biomass burning at a high altitude background site at Mt. Yulong (3410 m), China[J]. *Atmospheric Chemistry and Physics*, 2018, 18(21): 15687-15703.

Acknowledgement

Researchers:

Tsinghua University

Professor Shijing Shuai, Dr Xiao Ma
Zhou Zhang, Shuai Liang, Wenbin Zhang
Professor Yongliang Ma, Dr Yinzhi Zhang

Beijing University

Professor Min Hu, Dr Song Guo
Limin Zeng, Lidong Liu, Yiong Yu, Kai Song

The work is sponsored by China NSFC Key Project 51636003 and EPSRC EP/N021746/1

Thank you for your attention