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

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Outline

• Motivation and background

• Methodology

• Results and discussion

• Conclusions
Research background

- GDI vehicle has more particle emissions

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

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

- **Soot formation and oxidation**
  - Chance to form solid nanoparticles in high-ash-particle condition
- **Ash condensation**
  - Leaving exhaust tailpipe
  - SOF nucleation and growth
  - On-road newly-formed aerosol—abortion and aging
- **Process**
- **Pressure**
  - 150bar
  - 20bar
- **Temperature**
  - 2500K
  - 1500K
  - 600K
  - 330K
  - 300K
- **Dilution ratio**
  - 0
  - 10
  - 100
- **Object**
  - In-cylinder dry soot and ash
  - PM and VOCs evolution in exhaust system
  - Tailpipe PM/VOCs emission and diffusion
  - Secondary conversion of gaseous emissions in atmosphere
- **Time**
  - 2ms
  - 10ms
  - 0.5s
  - 0.6s
  - After 2s
In exhaust and atmosphere conditions, how GDI soot and particle evolve

Particle mode evolution mechanism in-cylinder and exhaust system
Connection of primary and secondary particle model
Gaseous component condensation, conversion and secondary particle formation mechanism at tailpipes and atmosphere

In-cylinder soot formation and influence factors of GDI engines
In-cylinder soot formation and influence factors of GDI engines

Engine test bench and optical diagnosis test experimental research
Simulation research on in-cylinder soot formation/oxidation and evolution

Particle evolution in exhaust systems of GDI engines
Particle evolution in exhaust systems of GDI engines

Engine test bench and aftertreatment experimental research
Simulation research on particle formation and evolution in the exhaust system

Particle and gas evolution mechanism at near-field of exhaust tailpipe plume
Particle and gas evolution mechanism at near-field of exhaust tailpipe plume

Vehicle on-road sampling or air-bag offline sampling experimental research
Simulation research on particle gas/solid phase evolution at near-field of exhaust tailpipe

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

Smoke box and atmosphere sampling experimental research
Simulation research on particles evolution and gaseous emission conversion in atmosphere

To reveal the evolution mechanism and build the model of primary and secondary particles of GDI vehicles
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.
Gas temperature changes dramatically in the exhaust pipe, where coagulation, condensation may occurs, resulting in particle components, morphology, mode variations.
Particle evolution inside exhaust system

Temperatures of sample positions

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). Method 2 has faster calculation speed (increase 50%) and more data (increase 100%).

**Image processing**

- Origin image
- Histogram balance
- High-pass filtering
- Binaryzation
- Skeletonization
- Remove short stripes
- Zoom in

**Graph:**

- Origin data
- Method 1
- Method 2

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
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.
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

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

Sample along plume

Dilution system

Smoke box

PAM Reactor

Primary particle

Secondary particle

Evolution of particles and engine-out gaseous emissions in atmosphere

Yield way to estimate SOA (impact of S/IVOC)

- OH exposed quantity, OH day
- Effects of NOx on SOA
- Spectrum
- Density
- Chemical component
- Calibrate AMS m/z 44
- Total mass
- SOA (solid/semi-liquid/liquid)

 PTR-ToF-MS
 O₃
 NOx
 SMPS
 CPMA
 AMS
 CO₂
 CO
 相态
Measurement at near-field of tailpipe plume

- 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 well on particle number, size and mass distributions
Simulation of particles evolution and gaseous components

- 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.

PM Size and Gaseous species or

SRM simulation
Experimental measurement

Start
Initialization
Discretize PM distribution
Nucleation
Condensation
Deposition
Coagulation
AM and NM statistics

$\frac{dN}{d\log D_p}$

Critical diameter
30 nm

$\frac{dN}{d log D_p}$

$\frac{dN}{d log D_p}$

$t_{current} < t_{terminal}$

End
Simulation of particles evolution

Comparison of simulation and experimental results

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

<table>
<thead>
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<th>Properties</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
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<tbody>
<tr>
<td>Aromatics (%v/v)</td>
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<td>28.5</td>
<td>36.7</td>
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<tr>
<td>Olefins (%v/v)</td>
<td>4.1</td>
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Summary and Main Conclusions

- 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)


Publications (2)


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