Particle Formation in Premixed and Diffusion Flames

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Lecture outline

- Particle formation revisited
- Pre-mixed flames
  - particle formation
  - diagnostics
- Electric field assisted particle formation
- Diffusion flames
  - flame types
  - Particle formation in vapor-fed flames
Particle formation & growth – key steps

Chemical reaction

Source of monomer species

Nucleation

Formation of clusters

Coagulation

Spherical particles form via particle-particle collisions

Aggregation

Collisions between spherical particles form chains

\[ \text{TiCl}_4 + 2\text{O}_2 \rightarrow \text{TiO}_2 + \text{Cl}_2 \]

Decreasing number concentration

Increasing size and mass
Particle formation & growth – in flames

Chemical reaction

Nucleation

Coagulation

Aggregation

T (K)

Particle formation & growth

- Nucleation
- Aggregation
- Coagulation
- Chemical reaction
Premixed flames

- Simple construction but particle formation in these flames is narrowly controlled.
- Safety is an issue.
- Excellent for basic understanding and for manufacture of a specific product day in and day out.
Monitoring particle dynamics by *intrusive* thermophoretic sampling

- **Burner**
- **Iris**
- **Detector**
- **Filter**
- **Hood**
- **Control box**
- **IR**
- **FTIR**
- **ε** (Detector)
- **Shift N₂**
- **CH₄, O₂, N₂**
- **HMDSO in N₂**

**Fourier transform infrared (FTIR) spectrometer**
Thermophoretic particle sampler
(original design by Dobbins and Megaridis, 1987)

5 bar N$_2$ pressure

$\text{t}_{\text{res}} = 50 \text{ ms}$
Particle size analysis in the flame

Thermophoretic Sampling
(Height: 33 mm)

Image Analysis

TEM

Average primary particle diameter, nm

42 ± 11 nm
Sampling position

Filter

Hood

Control box

Burner

Shield N₂

CH₄, O₂, N₂

HMDSO in N₂

N₂
TiO$_2$

\textbf{SiO}_2

SiO$_2$

Electrically assisted synthesis of nanoparticles


Evolution of TiO$_2$ particle growth

Diffusion flames

- Simple construction but particle formation in these flames is a complex system
- Requires detailed understanding of key processes and their interaction
Diffusion flame

Premixed flame
Diffusion flame

- Turbulent diffusion flames are frequently used in industry
- Safety
  - Fuel and oxygen do not mix until furnace
- Scale up
  - Up to several tonnes per hour
- Simplicity
- Flexibility in controlling product particle characteristics
Counter-flow Diffusion Flames

Counter-flow Diffusion Flames
Counter-flow diffusion flames


http://www.engr.uconn.edu/~renfro/facilities.html
Co-flow diffusion flames

- Simplicity
  - Safe
  - Concentric pipes
  - Fuel, air and precursor in each pipe
# Materials made in vapor-fed flames

<table>
<thead>
<tr>
<th>Product</th>
<th>Volume t/y</th>
<th>Ind.Process (dominant)</th>
<th>Use (exemplary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon black</td>
<td>8 M</td>
<td>Vapor Flame</td>
<td>Inks, Rubber</td>
</tr>
<tr>
<td>Titania</td>
<td>2 M</td>
<td>Vapor Flame</td>
<td>Paints</td>
</tr>
<tr>
<td>Fumed Silica</td>
<td>0.2 M</td>
<td>Vapor Flame</td>
<td>Toothpaste, Tires</td>
</tr>
</tbody>
</table>

*Chemical Economics Handbook, 2001; direct industrial quotes*

- A wide range of interesting applications
- Significantly large commercial markets
Wolfhard-Parker slot burner: 2-D flame combustion of hydrocarbons

Radial Distribution of Gaseous Species Concentrations

- Hydrocarbon Combustion in a Diffusion Flame
- Measurement by Mass Spectrometry

Radial distribution of the velocities

- Laser velocimetry with parallel beams and Al-Oxide particle seeds

Radial Temperature Distribution along the Diffusion Flame Axis (co-annular burner)

- thermocouple measurements

Axial Evolution of Radial Distribution of Light-scattered by Soot along a Diffusion Flame

A few possible configurations…

CFD flow fields

Particle formation in vapor-fed flames

- Gaseous Precursor
- Molecules
- Nucleation
- Primary Particles
- Coagulation and Sintering
- Agglomerated Particles
- Non-Agglomerated Particles

100nm
Lecture summary

- Particle formation revisited
- Particle growth in premixed flames
  - axial and radial effects
  - electrical field effects
- Diffusion flames
  - Counter-flow and co-flow flames
  - Species distribution

Further reading


