Thermal management in porous ceramic particulate filters: Opportunities and consequences of plasma technology solutions for particulate filter regeneration [Powerpoint]

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Thermal Management in Porous Ceramic Particulate Filters

Opportunities and Consequences of Plasma Technology Solutions for Particulate Filter Regeneration

Presentation Outline
1. Introduction
2. Particulate Filter Substrates
3. Plasma Thermal Regeneration
4. Plasma Heat Generation Measurements
5. Substrate Limits and Damage
6. Physical Regeneration

Dr. Andy Williams
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8th April 2016
Introduction

- Particulates from combustion sources are considered harmful and are therefore regulated.
- Particulate filters are proven technologies capable of >99% reduction of particulate emissions, at the expense of fuel consumption and cost.
- Filters typically require frequent regeneration (cleaning) to maintain acceptable pressure drops which is commonly achieved through heating (oxidation).
- Direct heating of the particulates should offer a lower energy solution than heating the air which flows through the substrate.
Introduction

- Prof. Colin Garner explored microwave heating in the mid 1980s
- Prof. Garner and Dr John Harry explore opportunities for electrical plasma regeneration
- 3 major projects and 4 PhDs since 2000 contributed to two unique regeneration methods

Acknowledgements:
Prof. Jon Binner, Prof. Colin Garner, Dr Karola Graupner, Dr John Harry, David Hoare, Prof. Mike Kong, Dr Karim Ladha, Dr Davide Mariotti, Dr John Proctor.

Microwave Regeneration:
Focuses energy in PM;
Slow (electrical power limits);
Requires bypass.

Electrical Plasmas:
High power density;
Rapid heating therefore no bypass needed;
Low power;
Low cost.
Background: Particulate Filter Substrates

Gelcast Ceramic Foams

Metallc Membranes

Monolithic Wall Flow Filters

Fibrous Filters
### Background: Plasma Regeneration of Filters

#### Glow Discharge
- single current path
- two discharge roots
- well defined discharge column
- Proctor, 2006, Loughborough University PhD Thesis

#### Corona Discharge
- multiple current paths
- one well defined root
- divergent discharge column

#### Dielectric Barrier
- multiple current paths
- no discharge roots
- no visible discharge column

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**Regeneration Rate (g/hr)**

- Proctor, 2006, Loughborough University PhD Thesis

**Regeneration Efficiency (g/kW h)**

- Low Glow
- Low Corona
- Low DBD

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Loughborough University

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15 mm
Inserted electrodes and Autoselectivity of electrical plasmas enables regeneration (cleaning) of almost all of the filter volume.
Plasma Heat Generation Measurements

Calorimetric measurements:

Electric power consumption measurements:
Ceramic Foams: Damage

- In a 2000 hour powertrain system life with 200 regenerations, any location in the filter will be exposed to the plasma for ~60 seconds.
- Failure modes of interest are typically those which can occur in a single exposure.

Melting in Cordierite samples:

Thermal shock in Alumina:

Distributed PM means heating of the substrate is unavoidable:
Potential for Damage

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W m(^{-1}) K(^{-1}))</th>
<th>Density (kg m(^{-3}))</th>
<th>Specific Heat Capacity (J kg(^{-1}) K(^{-1}))</th>
<th>Melting Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordierite</td>
<td>1.59</td>
<td>2100</td>
<td>753.6</td>
<td>1650</td>
</tr>
<tr>
<td>Alumina</td>
<td>8.63</td>
<td>3980</td>
<td>1103.4</td>
<td>2050</td>
</tr>
<tr>
<td>Zircon</td>
<td>4.2</td>
<td>4600</td>
<td>538</td>
<td>2400</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>59.8</td>
<td>3210</td>
<td>31.4</td>
<td>2700</td>
</tr>
<tr>
<td>Cordierite Foam</td>
<td>0.25</td>
<td>420</td>
<td>754.1</td>
<td>1650</td>
</tr>
<tr>
<td>Alumina Foam</td>
<td>1.17</td>
<td>796</td>
<td>1103.3</td>
<td>2050</td>
</tr>
<tr>
<td>Zircon Foam</td>
<td>0.62</td>
<td>920</td>
<td>538.4</td>
<td>2400</td>
</tr>
<tr>
<td>Silicon Carbide Foam</td>
<td>8.57</td>
<td>642</td>
<td>32.6</td>
<td></td>
</tr>
</tbody>
</table>


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![Graphs showing the relationship between power density and duration of discharge before onset of melting, and input energy required to reach 10,000 K material temperatures vs. power density.](image)
## Heat Generation in Constricted Plasma

<table>
<thead>
<tr>
<th>Region</th>
<th>Input Heat Flux (W.m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge column (constant)</td>
<td>2.72 x 10⁹</td>
</tr>
<tr>
<td>Through-filter (0 ≤ t &lt; 160 ms)</td>
<td>1.48 x 10¹⁰</td>
</tr>
<tr>
<td>Through-filter (t ≥ 160 ms)</td>
<td>3.70 x 10¹⁰</td>
</tr>
</tbody>
</table>

![Graph showing heat flux over time](graph.png)

- **Constant Power**: 4.2 W
- **Heat Flux**: 6 W
- **Time**: 0.2 s
- **Power Input**: 2 W
- **Filter + Column**: 0.8 W
Melting leads to collapse of porous structure affecting filtration as well as plasma power consumption.

PM cake layer ~ 113 μm

Thermal lag in the substrate allows more rapid PM heating than substrate.
Thermal Regeneration: Challenges and Opportunity

- Rapid heating desirable for efficiency
- Cooling needed for autoselectivity recovery

Useful temperatures

- Small margins exist between rapid oxidation (single strike) and substrate damage due to variations in pore and flow structures
- Higher working temperatures will give more margin and therefore allow fewer discharge events for a given regeneration
- Typical electrical power consumptions are still too high: ~2 kW for automotive filters.
Physical Regeneration

Opportunities arise from:
- Removed need for high operating temperatures
- Removed existing packaging constraints
- Removed ash constraints
- Maintains high filtration efficiency after regeneration
Summary

- Regeneration of particulate filters is needed to maintain acceptable pressure drops.
- For oxidation, we want to heat the PM and adjacent air. Typically we expend our energy heating the bulk air flow unnecessarily.
- Localised rapid heating with electrical plasmas allows rapid regeneration, however to be effective, alternative non electrically conductive substrates are needed that can operate at higher temperatures.
- Pulsed plasmas enable physical regeneration thereby removing the need for heating and opening an avenue for new, lower temperature, lower cost substrates.
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Opportunities and Consequences of Plasma Technology
Solutions for Particulate Filter Regeneration

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