PM/BC Reduction by DPF and wet-ESP for marine ship engines: Recent R&D in Korea

Sunho Park
Associate Professor
Department of Mechanical Engineering
Dankook University
Republic of Korea

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Outline

1. Background

2. R&D Overview

3. DPF for 400kW Ship Engine

4. Wet-ESP for 3MW Ship Engine

5. Summary and future plan
1. Background

Speaker's research at Dankook University

Synthesis and Characterization of PM

- High OC content
- Low OC content
- PM from ship (HFO)

Animal Exposure

VOC Removal by Plasma

Optical Diagnostics: Soot in Flame

Burner Design

Flame Stabilization

- CH4 392.3 sccm
- N2 1000 sccm

5th ICCT Workshop September 2018, SF
1. Background

Air pollutants from ship and their climate effects

Why is Greenland's ice getting darker?
1. Background

Particulate Matters

Schematic of diesel PM

<table>
<thead>
<tr>
<th>Main fractions</th>
<th>Sub-category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid fraction (SOL)</td>
<td>- Elemental carbon</td>
</tr>
<tr>
<td></td>
<td>- Ash</td>
</tr>
<tr>
<td>Soluble organic fraction (SOF)</td>
<td>- Organic material derived from L.O.</td>
</tr>
<tr>
<td></td>
<td>- Organic material derived from Fuel</td>
</tr>
<tr>
<td>Sulfate particulates (SO₄)</td>
<td>- Sulfuric acid</td>
</tr>
<tr>
<td></td>
<td>- Water</td>
</tr>
</tbody>
</table>

Total particulate matter (TPM) = SOL + SOF + SO₄

Guan, 2015, J. Environ. Management
1. Background

IMO PPR Agenda

‘Consideration of the impact on the Arctic of emissions of Black Carbon from international shipping’

▶ We finalized the definition for Black Carbon,
▶ We have been identifying appropriate methods for measuring black carbon emissions, and
▶ We are considering possible control measures that reduce black carbon emissions from international shipping.
1. Background: Global Projects

**INNOVATIVE AFTER TREATMENT SYSTEM FOR MARINE DIESEL ENGINE EMISSION CONTROL**

- **Budget**: 3.465 M€
- **Duration**: 3 yr. (09/2011 ~ 08/2014)

**DEECON project**

**Heracles project**

**M/V Victoria (BP)**
- **Dimension**: 69.96 X 11.44 X 4.25 (LBD, m)
- **M/E**: MTU8V4000, 880 kW, 1,800 rpm

**Table:**

<table>
<thead>
<tr>
<th>Contents</th>
<th>NOx</th>
<th>PM</th>
<th>SOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine out emission</td>
<td>8</td>
<td>0.15</td>
<td>0.81</td>
</tr>
<tr>
<td>Emission with reduction tech.</td>
<td>0.2-2.2</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Reduction rate(%)</td>
<td>72.5-90.0</td>
<td>97.3</td>
<td>99.5</td>
</tr>
</tbody>
</table>

**Budget**: 86 M€ + 25 M€
- **Duration**: 119 months + 36 months

**The objectives of the HERCULES-2**
- Fuel flexible engine
- New materials
- Adaptive power plant
- **Near-zero emissions engine**

**Work package 8**
- 80% PM reduction with after-treatment system
- Adaptation and integration of after-treatment system (SCR on DPF)
1. Background

Recent government-supporting R&D in Korea

- Development of NOx reduction unit for 10,000 ps-class ship engines (2011~2017, Ministry of Oceans and Fisheries)
- Installation and proof of SOx scrubber for ships toward IMO global sulfur cap (2018~2021, Ministry of Oceans and Fisheries)
- EGCS for Tier III regulation and 0.1%-sulfur fuel (2012~2014, Ministry of Trade, Industry and Energy)
2. R&D Overview

Development of DPF and wet-ESP for ships

- 2012-2018, Ministry of Oceans and Fisheries

DPF system for sub-MW engine

- 400 kW marine diesel engine
- Diesel particulate filter
- Back pressure sensor
- Gas analyzer
- PM analyzer

Wet ESP system for MW engine

- <2 st. diesel engine HHI-MAN B&W 6S46MC-c7>
- 1,500 TEU container
- WET EP (3 MW BC/Sox after-treatment system)
2. R&D Overview

Basic Principles

- **Diesel Particulate Filter**
  - Schematic
  - Gas from engine outlet ➔ Filtered gas
  - Exhaust gases from the engine ➔ Filter walls
  - Front plug ➔ Rear plug
  - Soot deposit ➔ Filter walls
  - Purified exhaust gases ➔ Engine
  - Regeneration necessary

- **Wet Electro-static Precipitator**
  - Schematic
  - Corona discharge ➔ Electrode ➔ adsorption ➔ Corona discharge ➔ Water film
  - Particle charging ➔ Collector plate ➔ Water film
  - Electrode (-) ➔ Collecting Plate (+)
  - Flushing of collector plate necessary

- **Diesel Particulate Filter**
  - 13" coated substrate
  - 6" square substrates
  - 24" substrate
2. R&D Overview

Ship application characteristics and the R&D objectives

▶ Ship application characteristics

- High sulfur content in fuel results in SO$_2$ in exhaust gas and a high sulfate fraction in PM
  - Sulfur poisoning of catalyst, Corrosion of ESP electrode, etc.
- PM contains more SOF (soluble organic fraction)
  - Controlling regeneration of PM in DPF is harder, DOC functionality issue
- Size of the after-treatment system is much greater than the system for land vehicles
- Allowable back pressure is lower
- Ship stability issue

▶ Objectives: Not only deal with the issues in the above, but also satisfy the following conditions:

- Diesel Particulate Filter
  - 400 kW engine DPF
    - Back Pressure: < 100 mbar
    - PM/BC reduction: > 90 %

- Wet Electro-static Precipitator
  - 3MW engine ESP
    - Back Pressure: < 60 mbar
    - PM/BC reduction: > 90 %

...
2. R&D Overview

Test bench for marine engine emission and performance

- Low speed engine cell
- High/midium speed engine cell

Korean Register
Testing & Certification Center
Gunsan, Korea

- Fuel: Bunker-A (0.29%S), high sulfur diesel (0.34, 0.05%S), ULSD (< 10 ppmS)
- Engine: HHI-MAN 6S46MC (2-str., 7.4 MW), Doosan Infracore 4V158TIH (4-str., 403 kW)
- Test cycle: E2, E3 cycle from ISO 8178
2. R&D Overview

PM emission from the test engines

- 2-st 7.4 MW engine

- 4-st 400 kW engine (ULSD)
3. DPF for 400 kW ship engine

Part design and development

Pore former and microstructure of the substrate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pore former</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Graphite</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>1.3</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>50.1</td>
</tr>
<tr>
<td>Ave. pore size [µm]</td>
<td>6.7</td>
</tr>
<tr>
<td>Intrusion vol. [cc/g]</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Active regeneration burner

- Air flow controller
- Fuel injecting nozzle
- Flame control
- Ignition test
- Burner systemization
3. DPF for 400 kW ship engine

Test results

**DPF system for 400 kW engine**

<table>
<thead>
<tr>
<th>Experimental conditions (E2 &amp; E3 cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
</tr>
<tr>
<td>Power [kW]</td>
</tr>
<tr>
<td>Speed [rpm]</td>
</tr>
<tr>
<td>Torque [Nm]</td>
</tr>
<tr>
<td>Mode</td>
</tr>
</tbody>
</table>

**Gravimetric**

Ave. reduction: 84%

**FSN**

**Opacity**

Cycle E2 cycle E3 cycle

Power [kW] 403 302 202 101 403 302 202 101
Speed [rpm] 1,800 1,800 1,638 1,440 1,134
Torque [Nm] 2,139 1,604 1,069 535 2,139 1,763 1,337 849
Mode 1 2 3 4 1 2 3 4
4. Wet-ESP for 3MW ship engine

**Background research**

- **Electro-static precipitator**

  ![Electrostatic precipitator](image1)

  ![Graphs showing filter smoke number and soot concentration](image2)

  ![Graph showing particle number concentration](image3)

- **2-st 7.4 MW engine emission measurement**

  ![2-st diesel engine HHI-MAN B&W 8S46MC-C7](image4)

  ![Table showing experimental condition (E3 cycle)](image5)

  ![Graph showing number concentration and FSN](image6)
4. Wet-ESP for 3MW ship engine

Installation and test

<table>
<thead>
<tr>
<th>Engine Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power [kW]</td>
</tr>
<tr>
<td>Bore x Stroke</td>
</tr>
<tr>
<td>Cylinder number</td>
</tr>
<tr>
<td>Fuel cons. [kg/h]</td>
</tr>
<tr>
<td>Engine type</td>
</tr>
</tbody>
</table>

2st. diesel engine  
HHI MAN B&W 6S46MC-c7
Hydraulic Dyno.

Supporting frame installation

Pipe connection between EP and MW engine

WET EP  
(3 MW PM/BC after-treatment system)

Measurement of engine out emissions
Smoke meter
Engine monitoring: P, T, atm, back pressure...
4. Wet-ESP for 3MW ship engine

Test results

**PM/BC reduction**
- FSN method: 75-82%
- PAS method: 82-86%

**Back Pressure**
~ 38 mbar

**Gaseous emissions**
rarely removed
4. Wet-ESP for 3MW ship engine

Test result of the final product

- **PM/BC reduction**
  - FSN method:
    - Smoke (FSN): 91.4%
  - PSA method:
    - Soot concentration (mg/m³): 95.3% 95.7%

- **SO₂ reduction**
  - SO₂: 1266.6 ppm
    - CO₂: 4.4 ppm
    - SO₂/CO₂ ratio: 288.7 (6.668% S)
    - 93.4% 95.5%
  - SO₂: 1266.6 ppm
    - CO₂: 4.4 ppm
    - SO₂/CO₂ ratio: 329.7 (7.616% S)
    - SO₂: 1441.8 ppm
    - CO₂: 4.4 ppm
    - SO₂/CO₂ ratio: 329.7 (7.616% S)
    - 93.4% 95.5%

- **Performance of the final product**
  - Back pressure: 31 mbar < 60 mbar
  - SOx reduction: 97%
  - PM/BC reduction: 91.4% > 90%
5. Summary and future plan

- DPF system for sub-MW class and wet-ESP for MW class marine engine developed in Korea

<table>
<thead>
<tr>
<th>400 kW engine DPF</th>
<th>3MW engine ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Back Pressure</strong></td>
<td><strong>Back Pressure</strong></td>
</tr>
<tr>
<td></td>
<td>57 mbar</td>
</tr>
<tr>
<td><strong>PMBC reduction</strong></td>
<td><strong>PMBC reduction</strong></td>
</tr>
<tr>
<td></td>
<td>96 %</td>
</tr>
<tr>
<td><strong>Fuel Consumption increase &amp; Power loss</strong></td>
<td><strong>SOx reduction</strong></td>
</tr>
<tr>
<td></td>
<td>0.9 %</td>
</tr>
<tr>
<td></td>
<td>97 %</td>
</tr>
</tbody>
</table>

- Real ship installation and proof will be performed soon.

- **Real ship proof of the developed DPF system** (2018-2021, Ministry of Oceans and Fisheries)
  - Ship installation scheduled

- **Development of SCR on DPF system for 500 kW marine engines** (2018-2021, Ministry of Trade, Industry and Energy)
  - SCR catalyst coated filter
5. Summary and future plan

Control measures under consideration (IMO PPR CG)

- **Fuel Type**
- **Fuel Treatment**
- **Exhaust gas treatment**

**Diesel Particulate Filters (DPF)**

**Electrostatic Precipitators (ESP)**

**Selective Catalytic Reduction (SCR) with Diesel Particulate Filter (DPF)**

Covers both SCR combined with DPF in a serial connection, and SCR-F technology. The latter is a single device which has the functions of both SCR and DPF by coating SCR catalysts on a filter for DPF.
Thank you very much for your attention!

Sunho Park

Associate Professor of Mechanical Engineering
Dankook University
Republic of Korea

E-mail: sunhopark@dankook.ac.kr