Emissions Control Strategies from Ocean Going Vessels Effect on Black Carbon Emission Methods

Center for Environmental Research and Technology,
College of Engineering, University of California, Riverside

ICCT Third Workshop on Marine Black Carbon Emissions
September 7th and 8th 2016
Vancouver, British Columbia, Canada
Outline

- Background
- Objective
- Approach
- Results
- Discussions
MARPOL Annex VI is targeting 0.5% of sulfur in the fuel by 2020 internationally. Strict sulfur limits are in place in ECAs, and potential of increase ECAs.
Strategies to Control Sulfur Emissions

- Switch to MGO
- Install a Scrubber
- Switch to LNG/Dual Engine
- Avoid ECAs
- MARPOL Annex VI

### Bunker Prices ($/mt)

<table>
<thead>
<tr>
<th></th>
<th>HFO</th>
<th>MGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Average</td>
<td>277.50</td>
<td>546.50</td>
</tr>
<tr>
<td>Americas Average</td>
<td>280.00</td>
<td>588.50</td>
</tr>
<tr>
<td>APAC Average</td>
<td>287.50</td>
<td>551.00</td>
</tr>
<tr>
<td>EMEA Average</td>
<td>260.50</td>
<td>472.50</td>
</tr>
</tbody>
</table>

*mt stands for metric tons
*Information adopted from Ship&Bunker on Sep 1st
Scrubber System

- Both open and close loop System
- Typical Venturi scrubber and a cyclone separator
- Monitoring SO$_2$, CO$_2$, PH, PAH, and turbidity
### On Sea Scrubber Main and Auxiliary Engine

<table>
<thead>
<tr>
<th>Source</th>
<th>Engine Mfg.</th>
<th>Model</th>
<th>Engine Power kW</th>
<th>Run Hours</th>
<th>EGCS</th>
<th>Exhaust Fraction $^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>Mitsui B&amp;W</td>
<td>7L70</td>
<td>16,578</td>
<td>177,962</td>
<td>yes</td>
<td>93%</td>
</tr>
<tr>
<td>AE_1s</td>
<td>Wartsila</td>
<td>6R32D</td>
<td>2,105</td>
<td>70,096</td>
<td>yes</td>
<td>0%</td>
</tr>
<tr>
<td>AE_1p</td>
<td>Wartsila</td>
<td>6R32D</td>
<td>2,105</td>
<td>79,020</td>
<td>yes</td>
<td>7%</td>
</tr>
<tr>
<td>AE_2s</td>
<td>Wartsila</td>
<td>4R32BC</td>
<td>1.263</td>
<td>63,211</td>
<td>no</td>
<td>n/a</td>
</tr>
<tr>
<td>AE_2p</td>
<td>Wartsila</td>
<td>4R32BC</td>
<td>1.263</td>
<td>55,067</td>
<td>no</td>
<td>n/a</td>
</tr>
<tr>
<td>Boiler</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>no</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- Performed 4 loads on HFO fuel (1.9% S) pre and post scrubber
- Measured gaseous and PM emissions
- Measured BC via three methods
  - MSS: Light absorption-photoacoustic
  - FSN: Light absorption-optical
  - ECOC: Thermal/optical

---

q\(^2\) Performed 4 loads on HFO fuel (1.9% S) pre and post scrubber
q\(^2\) Measured gaseous and PM emissions
q\(^2\) Measured BC via three methods
q\(^2\) MSS: Light absorption-photoacoustic
q\(^2\) FSN: Light absorption-optical
q\(^2\) ECOC: Thermal/optical
Emissions Sampling System

ADF: Air Dryer Filter
DAH: Dilution Air Heater
FSN: Smoke Meter
MFC: Mass Flow Control
MFM: Mass Flow Meter
MSS: Micro Soot Sensor
PG350: Horiba Gas Analyzer

Designed by: Kent Johnson
Post Scrubber Sampling
# Test Sequence

<table>
<thead>
<tr>
<th>Day</th>
<th>Location</th>
<th>Special Notes</th>
<th>Deck</th>
<th>Source</th>
<th>Scrubber</th>
<th>Mode</th>
<th>ME Load</th>
<th>AE Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dock ¹</td>
<td>-</td>
<td>3</td>
<td>AE</td>
<td>Pre</td>
<td>4</td>
<td>0%</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>at-sea</td>
<td>-</td>
<td>2</td>
<td>ME</td>
<td>Pre</td>
<td>3</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>at-sea</td>
<td>-</td>
<td>2</td>
<td>ME</td>
<td>Pre</td>
<td>2</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>at-sea</td>
<td>High DR</td>
<td>2</td>
<td>ME</td>
<td>Pre</td>
<td>2</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>at-sea</td>
<td>-</td>
<td>2</td>
<td>ME</td>
<td>Pre</td>
<td>1</td>
<td>92%</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>at-sea</td>
<td>-</td>
<td>5</td>
<td>ME+AE</td>
<td>Post</td>
<td>1</td>
<td>92%</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>at-sea</td>
<td>-</td>
<td>5</td>
<td>ME+AE</td>
<td>Post</td>
<td>2</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>at-sea</td>
<td>High DR</td>
<td>5</td>
<td>ME+AE</td>
<td>Post</td>
<td>2</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>at-sea</td>
<td>-</td>
<td>5</td>
<td>ME+AE</td>
<td>Post</td>
<td>3</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>at-sea</td>
<td>No AE</td>
<td>5</td>
<td>ME-only</td>
<td>Post</td>
<td>1</td>
<td>92%</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>at-sea</td>
<td>CL Mode</td>
<td>5</td>
<td>ME+AE</td>
<td>Post</td>
<td>2</td>
<td>75%</td>
<td>50%</td>
</tr>
<tr>
<td>5</td>
<td>dock ²</td>
<td>-</td>
<td>5</td>
<td>AE</td>
<td>Post</td>
<td>4</td>
<td>0%</td>
<td>50%</td>
</tr>
</tbody>
</table>

¹ Day 1 dock 1
² Day 5 dock 2
### Preliminary Results: SO$_2$ Reduction

#### 96-99% of the SO$_2$ reduction

- SO$_2$/CO$_2$ ratio < 4.3
- SO$_2$ emission reduction makes the fuel equivalent to 0.1% sulfur
- Fuel sulfur rule is being met with scrubber system (on a SO$_2$ basis)

#### Diagram

- **SO$_2$ g/kWh**:
  - Pre: 6.61
  - Post: 0.10

- **SO$_2$ emission reduction**:
  - Pre: 98.45%
  - Post: 96.84%

- **SO$_2$/CO$_2$ ratio**:
  - Pre: 4.50
  - Post: 4.17

- **Fuel sulfur rule**:
  - Pre: 3.82
  - Post: 0.13

#### Graph

- **pH and % of total SO$_2$**:
  - SO$_2$H$_2$O
  - HSO$_3^-$
  - SO$_3^{2-}$

- **Equivalent % in the test fuel**:
  - Pre: 1.89%
  - Post: 0.029%

- **Engine Load (AE+ME)**:
  - 4% AE Only: 0.060%
  - 48%: 0.060%
  - 70%: 0.060%
  - 85%: 0.065%
Preliminary Results: Overall Sulfur Reduction

- Study done by Schneider et al. (2005) explained -
  Formation of nucleation mode particles from diesel exhaust occurs only under certain condition: high sulfur content and cooling effect.

- Insignificant removal of the sulfur in the PM
- Health impact on the nanosize sulfuric acid particle is not clear

<table>
<thead>
<tr>
<th>Engine Load (ME+AE)</th>
<th>SO4 µg/min*filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre Scrubber</td>
<td></td>
</tr>
<tr>
<td>48%</td>
<td>64.60</td>
</tr>
<tr>
<td>70%</td>
<td>131.47</td>
</tr>
<tr>
<td>85%</td>
<td>158.73</td>
</tr>
<tr>
<td>Post Scrubber</td>
<td></td>
</tr>
<tr>
<td>48%</td>
<td>64.00</td>
</tr>
<tr>
<td>70%</td>
<td>118.33</td>
</tr>
<tr>
<td>85%</td>
<td>160.33</td>
</tr>
</tbody>
</table>

*Same dilution ratio at each load

References:
Exhaust Plume
Equivalent Sulfur in the Fuel (gas + particle)

- 79-93% of the overall sulfur content reduction.
The scrubber is able to remove approximately 10% of the total PM, 30% on the OC, and 5% on sulfur PM.

The reduction of the BC carbon varies on the measurement method has a range of 20-40% of reduction by scrubber.

ISO Weighted Particle Reduction

<table>
<thead>
<tr>
<th>Combined Load (ME + AE)</th>
<th>Suggested Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>85%</td>
<td>0.22</td>
</tr>
<tr>
<td>70%</td>
<td>0.52</td>
</tr>
<tr>
<td>48%</td>
<td>0.21</td>
</tr>
<tr>
<td>4%</td>
<td>0.05</td>
</tr>
</tbody>
</table>
AE trends to have more BC emissions rate (g/kWhr) than ME, 5-10 times

Trend of BC emissions reduction by scrubber from AE, not ME

FSN and EC trend to have higher BC results than MSS

None of the instruments show a statistically difference

<table>
<thead>
<tr>
<th>TTEST</th>
<th>MSS</th>
<th>FSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSS</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>FSN</td>
<td>0.8556</td>
<td>x</td>
</tr>
<tr>
<td>EC</td>
<td>0.2436</td>
<td>0.2740</td>
</tr>
</tbody>
</table>

*AE included
BC Measurement Comparison – FSN vs MSS

Sample Range has a big effect on correlation curve

- ME+AE data shows a high R² and good slope
- ME only shows a poor R² and low slope and high offset

Task 1 - Engine Testing
BC Measurement Comparison – EC vs MSS

- Lower EC element in a higher sulfur filter, 150 times lower than task 1.
- High sulfur content on the quartz filter made the pyrolyzation of the OC happens at low temperature, change OC-EC split point.

**Task 1 - Engine Testing**

<table>
<thead>
<tr>
<th>Particles (µg/filter)</th>
<th>Task 1</th>
<th>Task 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>2 - 476</td>
<td>2 - 79</td>
</tr>
<tr>
<td>OC</td>
<td>5 - 515</td>
<td>54 - 498</td>
</tr>
<tr>
<td>SO4²</td>
<td>1 - 100</td>
<td>102 - 3380</td>
</tr>
</tbody>
</table>

Dilution Effect on BC Sampling

**MSS mg/m³**

- DR=8 Pre Scrubber: 0.5171 ± 0.03
- DR=20 Pre Scrubber: 0.4600 ± 0.01
- DR=8 Post Scrubber: 0.5378 ± 0.02
- DR=20 Post Scrubber: 0.5449 ± 0.01

**EC mg/m³**

- DR=8 Pre Scrubber: 1.4317 ± 0.02
- DR=20 Pre Scrubber: 1.0655 ± 0.03
- DR=8 Post Scrubber: 0.8588 ± 0.01
- DR=20 Post Scrubber: 1.1530 ± 0.02

---

**NOx (ppm)**

- Pre Scrubber ME 75%
- Post Scrubber ME 75%, AE 50%
Summary and Conclusion

- Nucleation mode sulfuric acid particles were formed in high sulfur fuel and cooling effect, which is not able to be removed by scrubber system. Scrubber system is not as effective as the fuel sulfur rule when considering the sulfur in the particle phase.
- Quartz filter based ECOC shown higher EC results when high amount of sulfur on the filter due to the pyrolyzation at low temperature effect the ECOC split point.
- MSS and FSN shown comparable correlation with task 1.
- Scrubber system able to meet $SO_2/CO_2$ (ppm\_v/%\_v) ratio less than 4.3, which corresponds to a 0.1% sulfur fuel.
Acknowledgment

Funding:

International Council for Clean Transportation (ICCT)

UCR Faculty, Student and Staff:

Dr. Kent Johnson, Dr. Wayne Miller, Dr. Thomas Durbin, Yu Jiang, Eddie O’Neil, Mark Villela, and Don Pacocha

Environmental Canada: Tak Chan

NRC-Canada: Kevin Thomson

AVL: Monica Tutuianu
Thank You for Your Attention
Preliminary BC Comparisons look good

- Concentrations very high for BC on AE engine (8x)
- ME+AE data shows a high $R^2$ and good slope (0.82)
- ME only shows a poor $R^2$ and low slow and high offset
- Concentrations for Scrubber vessel much higher than the Tier 2
- Prelim data suggest scrubber is reducing BC emissions.

**Graph:**

- $y = 0.8222x + 0.4162$
- $R^2 = 0.9929$

- $y = 0.5996x + 0.522$
- $R^2 = 0.1789$
Real Time Evaluation

**At Port Pre Scrubber AE**

- NOx (ppm)
- Sample Start Time
- CO2/100 (ppm)
- MSS

**Pre Scrubber**
- ME 75%
- ME MAX

**Post Scrubber**
- ME 75%, AE
- ME 50%, AE
- ME MAX

**At Sea Post Scrubber**
- ME 75%, AE 50%

**Real Time (6/24/2016)**

**Real Time (6/25/2016)**

**Real Time (6/26/2016)**

**Real Time (6/27/2016)**

- NOx (ppm)
- CO2 (ppm)
- MSS Soot (mg/m³)
First Ever **Tier 2** Main Engine Tested

- Performed VSR and 3 other loads on MGO fuel (0.03% S)
- Measured gaseous and PM emissions
- Measured BC via three methods (MSS, FSN, and EC)
- Used ISO reference sampling methods

<table>
<thead>
<tr>
<th>Source</th>
<th>Engine Mfg.</th>
<th>MY and Model</th>
<th>Engine Power kW</th>
<th>Run Hours</th>
<th>EGCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>Mitsui MAN B&amp;W</td>
<td>2011 12K98ME6.1</td>
<td>68,666</td>
<td>25,985</td>
<td>no</td>
</tr>
<tr>
<td>AE1</td>
<td>Daihatsu</td>
<td>2011 8DC32e</td>
<td>3,162</td>
<td>n/a</td>
<td>no</td>
</tr>
<tr>
<td>AE2</td>
<td>Daihatsu</td>
<td>2011 8DC32e</td>
<td>3,162</td>
<td>n/a</td>
<td>no</td>
</tr>
<tr>
<td>AE3</td>
<td>Daihatsu</td>
<td>2011 8DC32e</td>
<td>3,162</td>
<td>14,550</td>
<td>no</td>
</tr>
<tr>
<td>AE4</td>
<td>Daihatsu</td>
<td>2011 8DC32e</td>
<td>3,162</td>
<td>n/a</td>
<td>no</td>
</tr>
<tr>
<td>Boiler</td>
<td>Alfa-Laval</td>
<td>2011 n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>no</td>
</tr>
</tbody>
</table>
NOx Emissions in Compliance

- Vessel operated in “TC Cut Out” mode
- Shop trial performed in “Economy” mode
- Estimated ISO weighted NOx value of 15.5 g/kWhr
- ISO Cat 3 standard is 14.4 g/kWhr (dif of 7%)
- Engine is in compliance
PM Emissions Lowest at 40% Load

- PM emissions highest at VSR (~ 0.12 g/kWhr)
- Most of the PM is organic with some little BC
- Organic PM follows the trend of total PM
- Sulfate estimated at “tbd”
BC Emissions Lowest at high load and possibly still dropping

- BC emissions highest at 28% load
- BC emissions very low at 57% load
- Emission Factors at 57% load were 0.001 g/kWhr
- The Tier 2 BC EF at 57% load are 10 times lower than other tested (Tier 1 and Tier 0 vessels)
BC Measurement Methods Correlated Well

- R2 is high for both methods at 0.9 or greater
- FSN is higher than MSS and EC is lower.
- Raw stack concentrations very from 0.06 to 0.46 ug/m3
Project Background

- BC Measuring methods
  1. Light-absorbing property --- often referred to as BC
  2. Thermal or thermal/optical technique --- referred to as EC

Figure 1-1 Measurement of the Carbonaceous Components of Particles (SOURCE: EPA)
Preliminary Results: NOx Emissions

- 4% AE Only
- 48% EGCS Engine Load (AE+ME)
- 70%
- 85%

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>4% AE Only</td>
<td>14.96</td>
<td>8.64</td>
</tr>
<tr>
<td>48% EGCS Engine Load (AE+ME)</td>
<td>15.70</td>
<td>14.39</td>
</tr>
<tr>
<td>70%</td>
<td>16.93</td>
<td>14.39</td>
</tr>
<tr>
<td>85%</td>
<td>16.92</td>
<td>16.55</td>
</tr>
</tbody>
</table>
Dilution Effect on BC Sampling

- Dilution ratio has a larger effect at pre scrubber (exhaust temperature)
- Filter based EC has a larger derivation than MSS
- lower EC element in a higher S filter
Scrubber Operation Effect on BC Emissions

![Bar graph showing the effect of scrubber operation on BC emissions.](graph.png)