Variability in non-volatile particulate matter emissions of aero gas turbines caused by engine deterioration

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Context
- Aero gas turbines emit non-volatile particulate matter (nvPM aka soot) that affects human health, visibility and climate
- These nvPM emissions are a function of:
  - Engine operating condition
  - Fuel quality
  - Ambient condition
  - Engine deterioration
- While fuel quality and ambient effects will be considered in the new nvPM standard for aero gas turbines, there is a knowledge gap about engine deterioration
- Understanding deterioration is critical for accurate emission inventories

Objective
- Identify and quantify the potential deterioration effect on emissions

Methods

Data Collection
- nvPM and gaseous emissions data were collected in the engine test cell of SR Technics with a standardized sampling system:
  - Engine Test Cell
  - Instrumentation Room
  - nvPM Instrumentation

Engine Test Cell
- Single point measurements at one engine specific location
- Over 40 emission datasets were recorded as “piggy back” measurements on outgoing engine performance runs after repair or maintenance

Data Analysis
- Engines of the same variant with a specific thrust rating and combustor technology were selected to minimize other sources of variability:

| Engine # | # Datasets | Amb. Temperature (°C) | Amb. Pressure (bar) | Fuel Flow [kg/h] | Service Life (hrs) | Cycles | EST margin [%] |
|----------+-----------+----------------------+---------------------+-----------------+-------------------+--------+---------------|
| 1        | 1         | 8.2 – 8.5            | 962                 | 13.83           | 17355             | 7442   | 61.3           |
| 2        | 1         | 17.4 – 24.2          | 946                 | 14.11           | 36210             | 17133  | 51.7           |
| 3        | 1         | 14.3 – 16.4          | 964                 | 14.11           | 31804             | 15054  | 58.1           |
| 4        | 1         | 19.0 – 23.5          | 972                 | 13.98           | 32910             | 16054  | 53.7           |
| 5        | 6         | 1.5 – 17.8           | 960 – 970          | 14.14           | 32297             | 15291  | 68             |

- Emission indices were calculated using a carbon balance:
  \[ E_{\text{nvPM}} = \frac{\text{CO}_2}{4} \times \text{Fuel Flow} \times \text{Fuel C content} \]

- Ambient temperature correction was performed according to:
  \[ E_{\text{nvPM,corr}} = E_{\text{nvPM}} \times \frac{\text{T}_{\text{ref}}}{\text{T}_{\text{measured}}} \]

- Fuel corrections were performed using the hydrogen mass content (H) of the fuel according to:
  \[ E_{\text{nvPM,corr,hydrogen}} = E_{\text{nvPM}} \times (q_0 + q_H \times \text{Fuel C content} - H_{\text{fuel}}) \]

- Where \( q_0 \) and \( q_H \) are the fitting parameters determined on the same engine variant and \( H_{\text{fuel}} = 14.1\% \). The maximum correction factor was 0.60.

Conclusions
- Only five engines with the same combustor technology and thrust rating could be compared apple to apple
- After the correction for ambient and fuel effects, which were less than 9% and 18%, respectively, the analyzed data indicated increasing emission trends for nvPM mass and number emissions with engine service hours
- Computed LTO emissions increased drastically (356%) for nvPM mass with engine service life (36210 hrs.), while the trend for number emissions was less clear
- Current aircraft emission inventories which are based on type certification data of new engines underestimate real-world nvPM mass emissions due to engine deterioration

Results and Discussion

Quality check: CO2 emissions
- CO2 data indicate a good sampling system performance for all tests
- Idle CO2 increases slightly due to bleed air extraction (which reduces engine core airflow)
- Few data points available for Engine 1-3

Corrected nvPM mass and number emissions
- All engines have the highest mass emissions at the highest fuel flow
- The typical «laying S» curve is observed for the number emissions
- Differences in emissions between engines are particularly observed at higher thrusts
- Differences between Engines 3, 4 and 5 lay within the uncertainty of the measurement (+/-15%)

Implications for the landing and take-off cycle
- Aircraft emissions are regulated for the total emissions in the landing and take-off (LTO) cycle, which assumes; 26 min taxing, 4 min approach, 2.2 min climb-out and 0.7 min take off operations
- The LTO emissions for the new engine were computed based on smoke number correlations (Details can be found in poster #19)

<table>
<thead>
<tr>
<th>Engine</th>
<th>Service Life (hrs)</th>
<th>Total LTO nvPM mass emissions [g]</th>
<th>% Change</th>
<th>% Change in nvPM mass emissions [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine 1</td>
<td>17355</td>
<td>11.74</td>
<td>+10</td>
<td>9.87×10^{-2}</td>
</tr>
<tr>
<td>Engines 3-5</td>
<td>32000</td>
<td>29.01</td>
<td>+244</td>
<td>1.38×10^{-2}</td>
</tr>
<tr>
<td>Engine 2</td>
<td>36210</td>
<td>42.2</td>
<td>+356</td>
<td>1.58×10^{-2}</td>
</tr>
</tbody>
</table>

- Engine deterioration plays a major role for nvPM mass emissions, while nvPM number emissions are less affected
- An exponential increase in nvPM LTO mass emissions with service live is indicated
- Current aircraft emission inventories therefore underestimate nvPM mass emissions drastically

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References: 1Brem et al., Environ Sci Technol 49 (22), 13149-13157. 2015, 2Durdina et al., MMTHCTHCCOCO-6 Environ Sci Technol 49 (22), 13149-13157. 2015, 3Sentyan et al., Environ Sci Technol. 51(6), 3534-3541. 2017

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