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

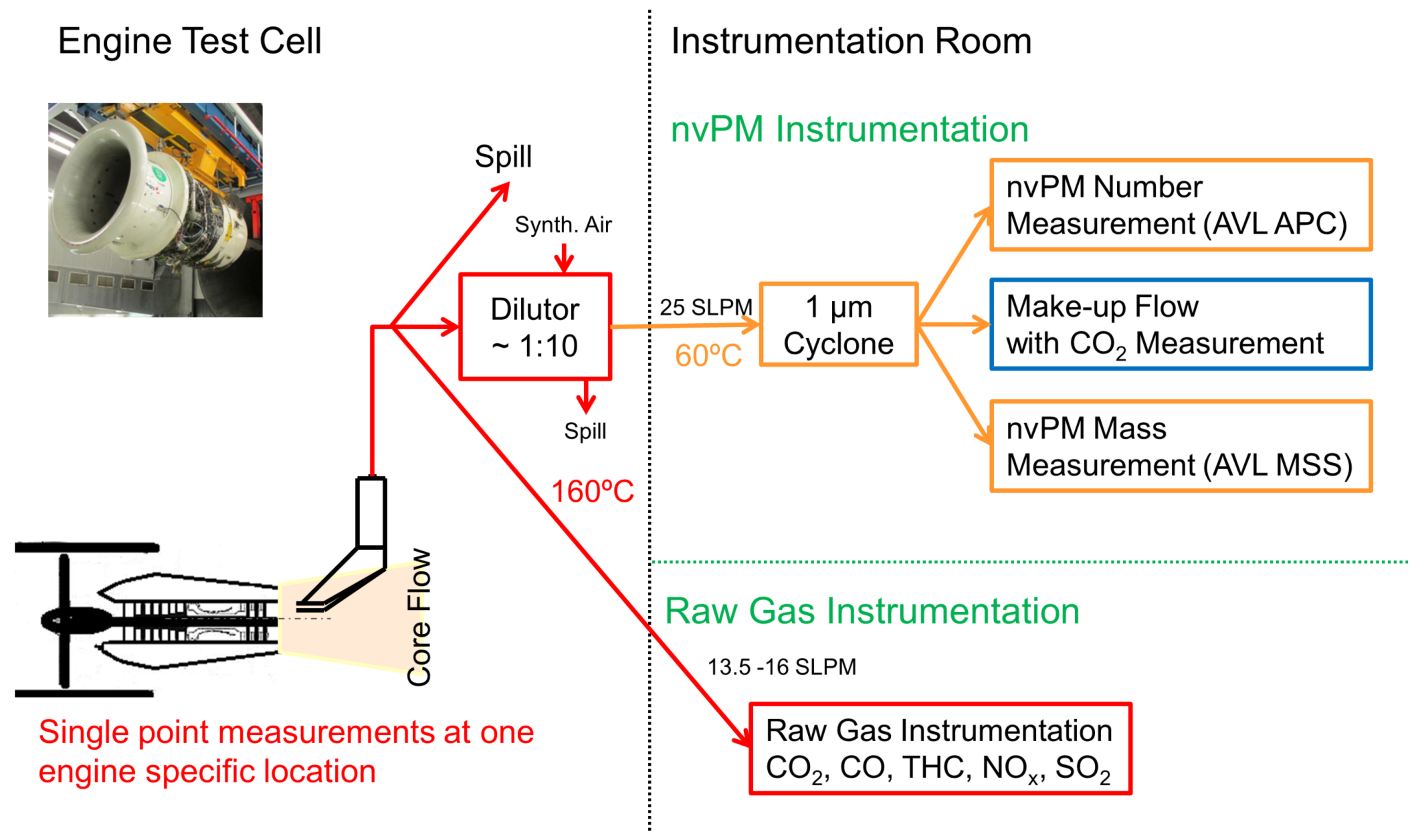
Objective

- 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:



- 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 (mbar)	Fuel H content (% m)	Service hours	Cycles	EGT margin (°C)
1	1	8.2 – 8.5	962	13.82	17505	7442	61.3
2	1	17.4 – 24.2	964	14.1	36210	17133	51.7
3	1	14.3 – 16.4	964	14.1	31804	15064	58.1
4	1	19.0 – 23.5	972	13.96	32910	16042	53.7
5	8	1.5 – 17.8	965 - 976	14.14	32297	15271	68

- Emission indices were calculated using a carbon balance:

$$EI\_nvPM_{Mass} = \frac{BC_{Mass} \times 10^6}{\left([CO_2]+[CO]-[CO_2]_{Background}+[THC]-[THC]_{Background}\right)(M_c+\alpha M_H)} \frac{0.082T}{P}$$

- Ambient temperature correction was performed according to:

$$EI\_nvPM_{Mass\_A\_ref} = EI\_nvPM_{Mass}\left(\frac{T_{ref}}{T_{measured}}\right)^{-0.04}$$

where T_{ref} was 15°C. This data was determined from multiple measurements on the same engine with the same maintenance status. No significant trend of emissions with ambient pressure could be determined in the data collected for the same dataset. The maximum correction factor was 0.91.

- Fuel corrections were performed using the hydrogen mass content (H) of the fuel according to:

$$EI\_nvPM_{Mass\_F\_corrected} = EI\_nvPM_{Mass}(\alpha_0+\alpha_1 F_{rel})(H-H_{corrected})$$

where α_0 and α_0 are fitting parameter determined on the same engine variant[1] and $H_{corrected}$ was 14.14%. The maximum correction factor was 0.82.

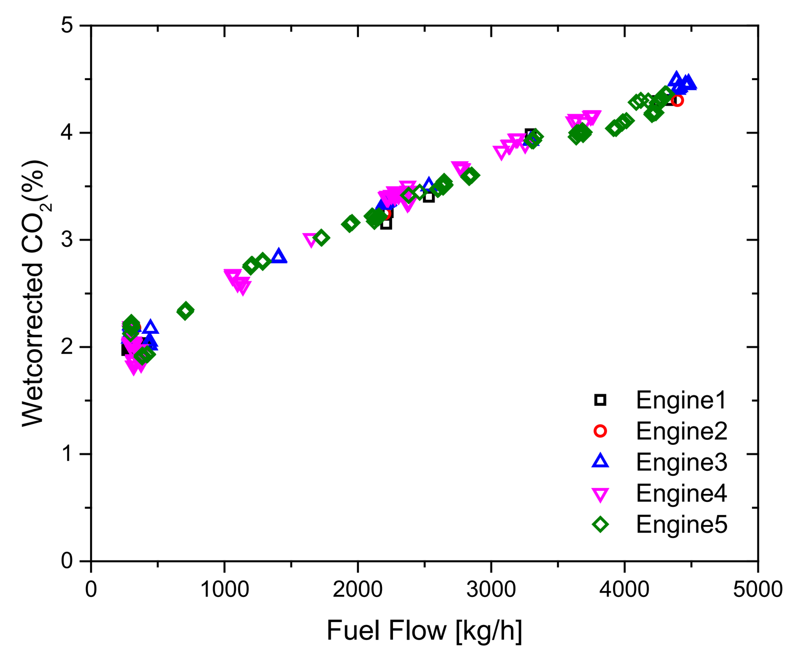
Conclusions

- 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

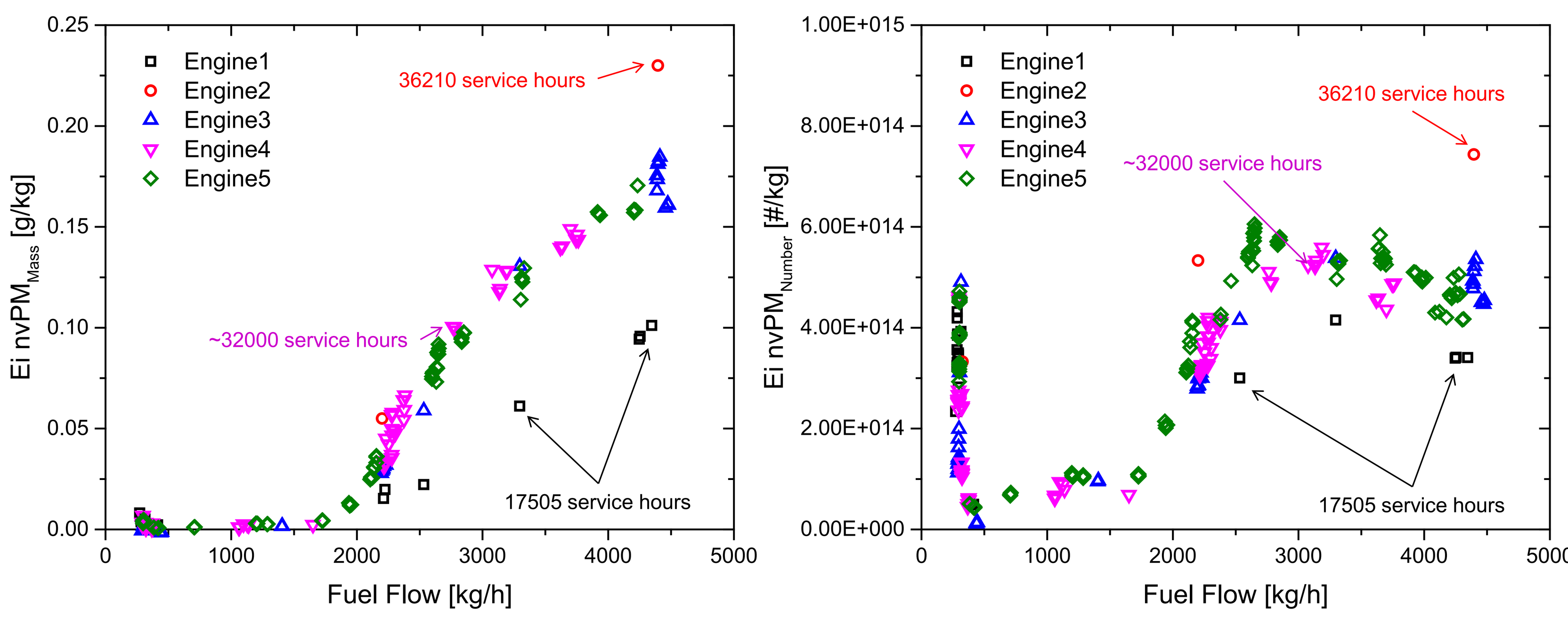
Results and Discussion

Quality check: CO_2 emissions

- CO_2 data indicate a good sampling system performance for all tests
- Idle CO_2 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 taxiing, 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)

Engine	Service hours	Total LTO $nvPM_{Mass}$ Emissions (g)	% Change $nvPM_{Mass}$	Total LTO $nvPM_{Number}$ Emissions (#)	% Change vPM_{Number}
New	1000	11.85	0	$1.33*10^{17}$	0
Engine 1	17505	13.74	+16	$9.87*10^{16}$	-25
Engines 3-5	32000	29.01	+244	$1.36*10^{17}$	+2
Engine 2	36210	42.2	+356	$1.95*10^{17}$	+47

- 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: [1]Brem *et al.*, Environ Sci Technol 49 (22), 13149-13157. 2015, [2]Durdina *et al.*, Environ Sci Technol. 51(6), 3534-3541. 2017

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