Influence of Ambient Temperature on the PM Emissions from a Gas Turbine Engine

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Introduction:

During Project AAFEX, PM emissions measurements were conducted on a CFM56-2C1 gas turbine engine in January 2009 in Palmdale CA. The engine was mounted on a NASA DC-8 aircraft, which was parked on the runway, and emission samples were extracted at the engine exit plane (1m), in the near field (30m), and in the advected plume (145m). The engine was operated at several power levels, and burned several fuels: JP-8, a Fischer-Tropsch fuel derived from natural gas (FT1), and a second Fischer-Tropsch fuel derived from gasified coal (FT2). In addition to these fuels, 50:50 blends of the Fischer-Tropsch fuels and JP-8 were also studied. Wide variations in ambient temperature, especially between early morning and late afternoon were experienced during the campaign. This report summarizes and describes the results of AAFEX, in terms of the influence of ambient temperature on total PM emissions at the exit plane of a CFM56-2C1 engine.

Instrumentation:

The instrumentation onboard the Missouri S&T mobile laboratory to sample emissions at the engine exit plane consisted of the Cambustion DMS500, a state-of-the-art fast particulate spectrometer, to gather real-time size distribution information and total concentration of engine exhaust PM; a scanning differential mobility analyzer (SDMA) (TSI model 3071), to measure PM size distributions; a TSI condensation particle counter (CPC) (TSI model 3022) to measure total number concentration; a fast response carbon dioxide (CO_2) detector to monitor sample dilution and establish emission factors.

Methodology:

In order to study the impact of temperature variation on PM emissions, two subsets of the entire AAFEX data set were selected, in which the fuel type and probe position were held constant while engine fuel flow (surrogate for power) and ambient temperature varied. The first data set chosen was for the reference fuel, JP-8, and the second data set was for the FT1 fuel.

These data sets were organized into the form $\{T_i, FF_i, ap_{ni}, \delta ap_{ni}\}$, where

- FF_i denotes the fuel flow during the i-th measurement,
- ap_{ni} denotes the measured value of the n-th aerosol parameter during the i-th measurement,
  - n = 1 refers to Dgn (number-based geometric mean diameter)
  - n = 2 refers to Dgm (mass-based geometric mean diameter)
  - n = 3 refers to EIn (number-based emissions index),
  - n = 4 refers to EIm (mass-based emissions index).
- δap_{ni} denotes the uncertainty in the measurement of aerosol parameter ap_{ni}.

A set of temperatures $\{T_j, j=1,2,\ldots,J\}$ and fuel flow rates $\{FF_k, k=1,2,\ldots,K\}$ were selected which span the range of temperature and fuel flow rate represented in the data, and where possible fall near values where these parameters cluster. Two dimensional interpolation was employed to determine values for the aerosol parameter and uncertainty at these selected temperatures and fuel flow rates. A linear interpolation was accomplished with the software package Matlab. Application of the interpolation method resulted in an interpolated data set $\{T_j, FF_k, ap_{njk}, \delta ap_{njk}\}$. ap_{njk} denotes the interpolated value for the n-th aerosol parameter at temperature T_j and fuel flow rate FF_k; δap_{njk} is its associated uncertainty.

Results:

Figure 1 shows the dependence of EIn on temperature for fixed fuel flow rates for JP-8 over its full ambient temperature range. EIn is observed to decrease with increasing temperature at the lower fuel flow rate (2778 lbs/hr) and highest fuel flow rate (7685 lbs/hr), whereas it increases modestly with increasing temperature at intermediate fuel flow rates 3869 lbs/hr and 6597 lbs/hr. It is independent of temperature at the mid fuel flow rate, 5385 lbs/hr. The mass based emissions index shows temperature-fuel flow rate trends that are similar to those for EIn.

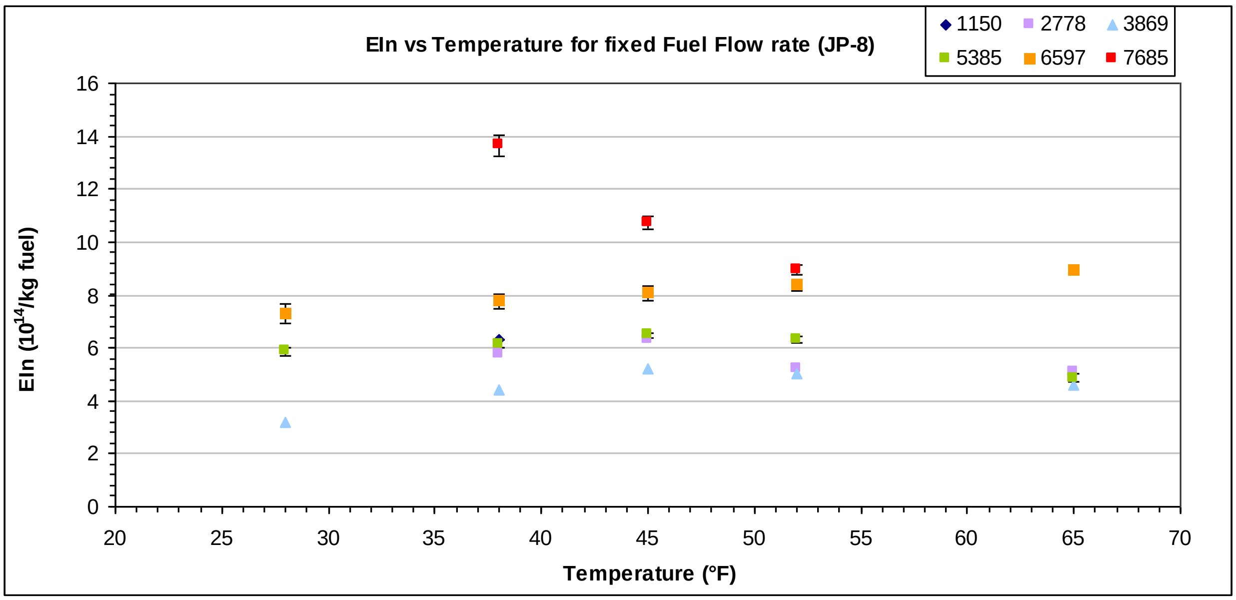

Figure 1: Number based emission index as function of temperature and fuel flow rate for JP-8

Two metrics that are useful to characterize the strength of temperature with regard to influencing PM emissions are: Mcr = maximum change ratio, and $\Delta\%$ = maximum percent change. For a fixed fuel type, fuel flow rate, and aerosol parameter, ap_n, Mcr_n is defined as

$Mcr_n = |ap_n(T_a) - ap_n(T_b)| / (\delta ap_n(T_a) + \delta ap_n(T_b))$,

where T_a and T_b are the temperatures which give the maximum value this ratio for fixed fuel flow rate. When $Mcr_n \geq 1$ the error bars for the two temperatures do not overlap and there is a statistically meaningful change in emissions. The parameter $\Delta\%$ gives the maximum percent change in aerosol parameter ap_n between two temperatures for the fixed fuel flow rate. Table 1 presents results for Mcr and $\Delta\%$ for JP8 combustion. Dgn does not show significant temperature change at the lowest and highest fuel flow rates (Mcr < 1), which yield percent changes of 2% and 3 %. It does produce significant changes, up to 26%, at all other fuel flow rates. The mass based geometric mean, Dgm, likewise shows no significant temperature dependence at its lowest fuel flow rate, 2778 lbs/hr, but exhibits a dependence at all higher fuel flow rates. The emission index parameters, EIn and EIm, show significant change, exceeding 100% variation in one case, due to the temperature dependency. Hence the influence of temperature is significant, and should be taken into account in the analysis of PM emissions data, before influences of other operating conditions, e.g. fuel type, and be determined. For FT1 combustion all aerosol parameters show significant temperature dependence (Mcr > 1), except for Dgm at the lower fuel flow rate conditions. Again, the aerosol parameters show large percentage changes due to temperature change, with several exceeding 100% change. The aerosol parameters for FT1 combustion exhibit a stronger temperature dependence than for JP-8 combustion; Δ%(FT1) exceeds Δ%(JP-8) 82% of the time, even though the JP-8 data spans a larger range of temperature change.

Table 1. Change in emissions from JP-8 combustion due to temperature variation.

ap	Fuel Flow rate (lbs/hr)	Mcr	Δ%
Dgn	1150	0.8	2
	2778	2.4	17
	3869	3.1	26
	5385	1.3	4
	6597	1.4	5
	7685	0.5	3
Dgm	1150		
	2778	0.6	21
	3869	3.9	28
	5385	3.2	7
	6597	2.7	5
	7685	1.3	2
EIn	1150		
	2778	11.9	22
	3869	17.4	48
	5385	6.6	29
	6597	3.3	20
	7685	8.5	42
EIm	1150	10.5	82
	2778	14.9	132
	3869	3.9	42
	5385	2.5	19
	6597	3.7	31
	7685	3.9	31

Conclusions:

PM emissions data was collected over an ambient temperature range of 28 to 65°F. Significant dependencies on temperature were observed, with Mcr's (maximum ratio of PM emission parameter change to experimental uncertainty) averaging 4.9 and 5.4, and ranging up to 17 and 26 for JP8 and FT1, respectively. The corresponding percentage changes in PM emission parameters due to temperature change, averaged 28 and 54 percent, and ranged up to 132 and 170 percent, for JP8 and FT1, respectively.

Acknowledgements:

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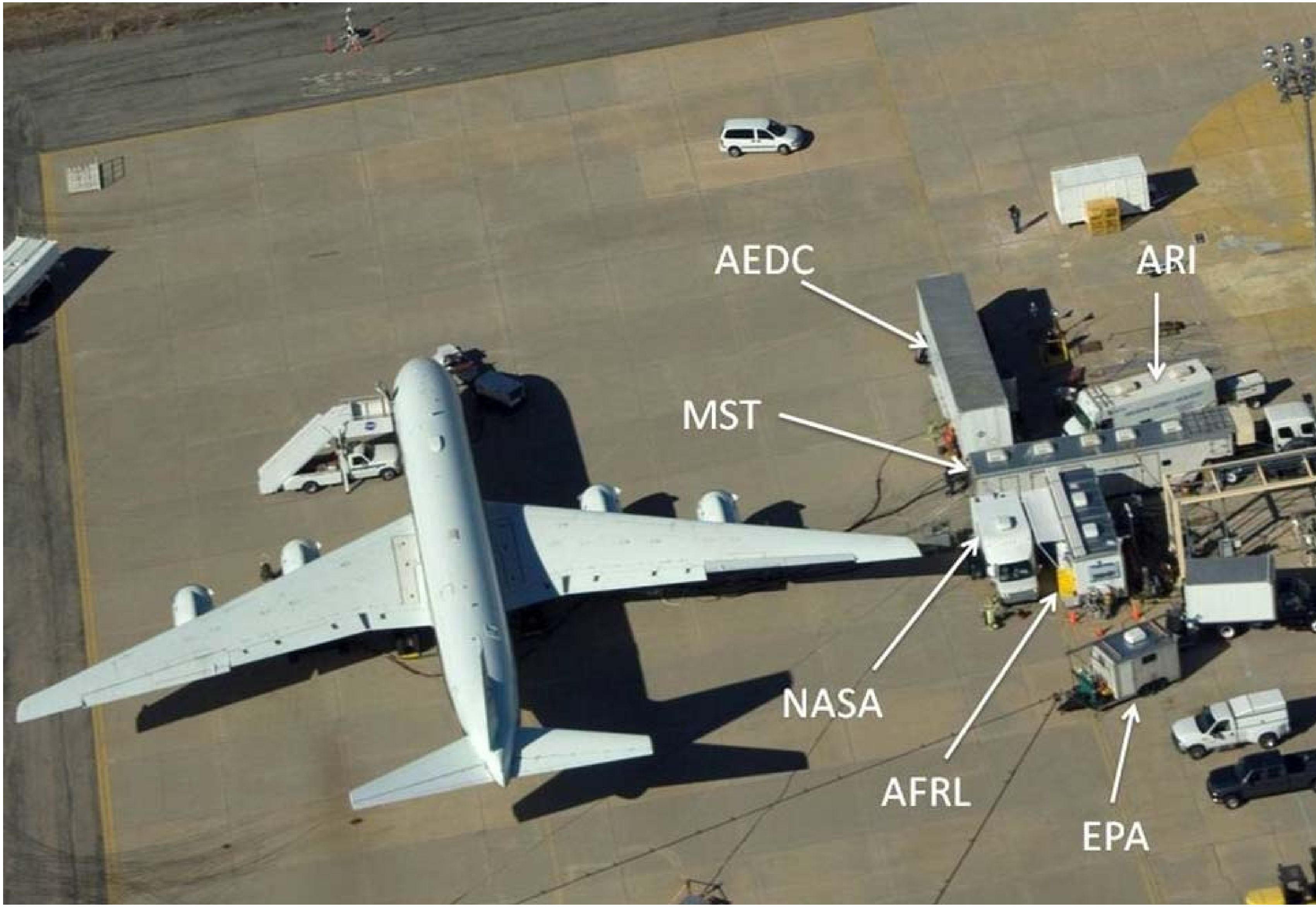
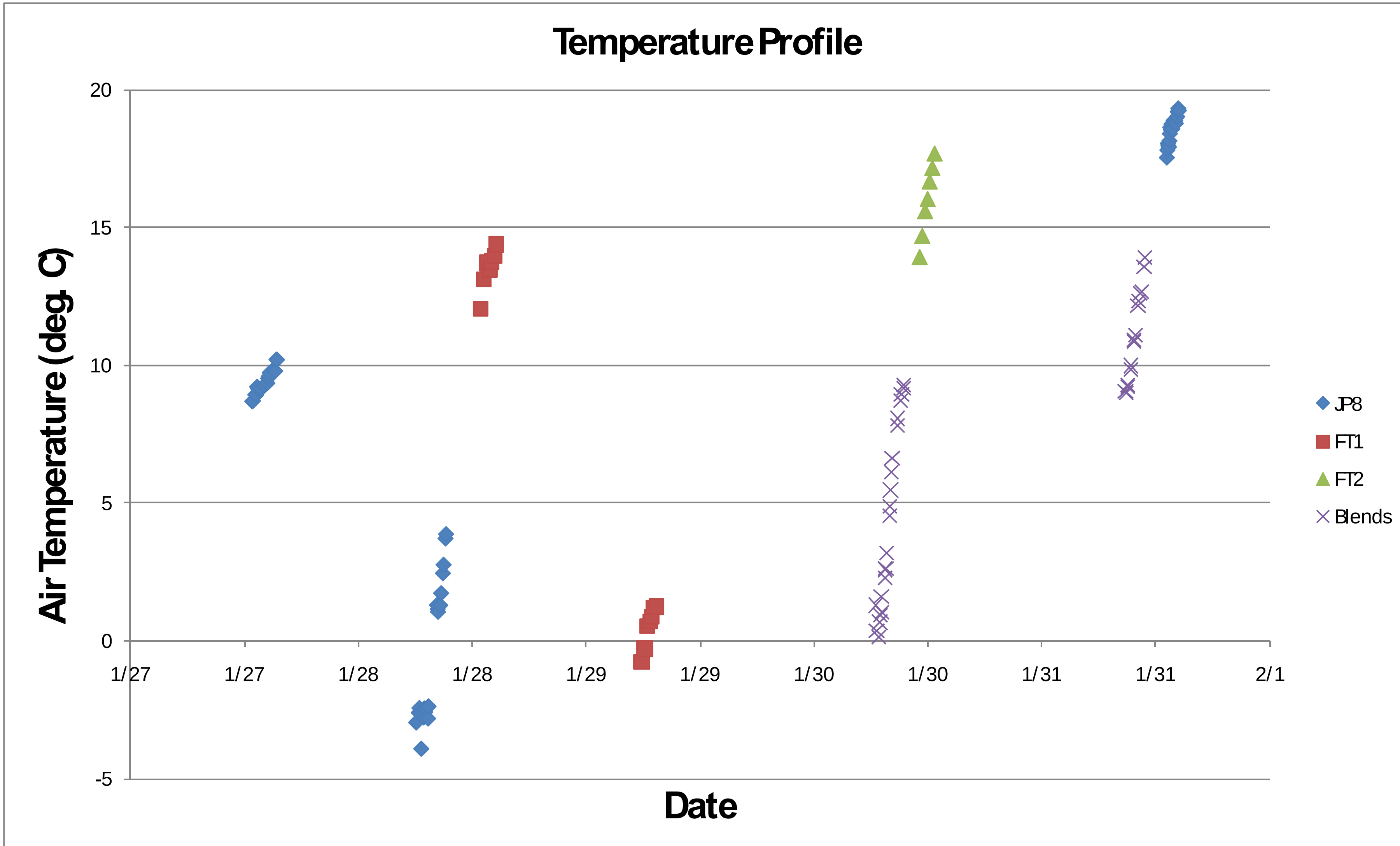

AEDC
ARI
MST
NASA
AFRL
EPA

PARTNER

PARTNER


RG1 FTIR AFRL
RG2 SMOKE AFRL
RG3 SMOKE AEDC
RP1 PARTICLE
RP2 PARTICLE
RG4 NASA
RP3 Particle
RP4 Particle
RG5 NASA
RP5 Particle
RP6 Particle
RG6 NASA
RG7 TEOM AFRL
RG8 LECO AFRL EC/OC
RG9 CMU
RG10 ARI



Temperature Profile
Air Temperature (deg. C)
20
15
10
5
0
-5
1/27
1/27
1/28
1/28
1/29
1/29
1/30
1/30
1/31
1/31
2/1
Date
JP8
FT1
FT2
Blends

Instrumentation

- Cambustion DMS500
  - Size Distribution
  - Total concentration
- TSI SDMA
  - Size Distribution
  - Total Concentration
- TSI CPC 3022
  - Total Concentration
- Fast response CO2

Methodology

- Selected two subsets of data
- Fuel JP8
  - Fixed probe position
  - Fuel flow (power) varied
  - Temperature varied
- Fuel FT1
  - Fixed probe position
  - Fuel flow (power) varied
  - Temperature varied
- Data $\{T_i, FF_i, ap_{ni}, \delta ap_{ni}\}$
  - i Run number
  - n=1 Number based geometric mean diameter
  - n=2 Mass based geometric mean diameter
  - n=3 Number based emission index
  - n=4 Mass based emission index

Methodology cont'd

- Interpolation – Matlab
  - Griddata
  - Meshgrid
- Input $\{T_i, FF_i, ap_{ni}, \delta ap_{ni}\}$
- Output $\{T_j, FF_k, ap_{njk}, \delta ap_{njk}\}$
- JP8 temperature range -2.2 to 18.3 C
- FT1 temperature range +1.1 to 14.4 C
- JP8 data interpolated 2nd time to cover FT1 T-range

Results

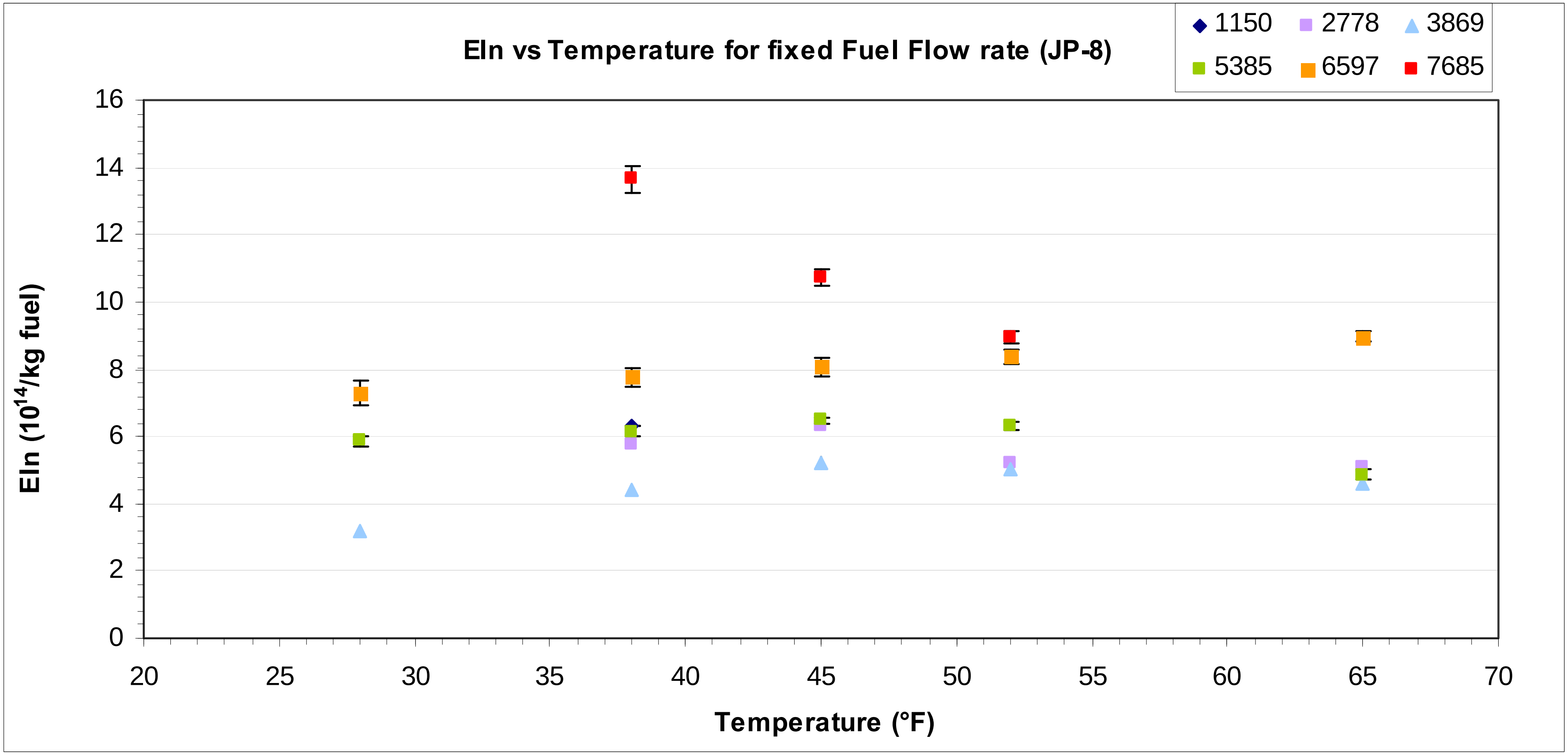
Dgn (nm)					
Fuel flow rate (lbs/hr)	Temperature (°F)				
	34	42	47	56	58
1150		11.46 ± 0.52	12.82 ± 0.73	15.70 ± 1.51	16.15 ± 1.89
2778	12.99 ± 0.94	13.53 ± 0.99	14.46 ± 0.96	16.09 ± 0.82	17.03 ± 1.82
3869	14.75 ± 1.84	13.93 ± 10.26	15.78 ± 7.77	19.10 ± 3.29	19.84 ± 2.30
5385	17.79 ± 0.42	17.27 ± 0.41	17.18 ± 0.37	17.01 ± 0.31	16.96 ± 0.32
6597	19.50 ± 0.35	20.09 ± 0.40	20.52 ± 0.42	21.25 ± 0.46	21.05 ± 0.38
7685		21.59 ± 0.46	22.59 ± 0.34	23.03 ± 0.37	

Dgm (nm)					
Fuel flow rate (lbs/hr)	Temperature (°F)				
	34	42	47	56	58
1150		142.53 ± 24.21	136.84 ± 29.37	126.60 ± 38.66	125.12 ± 38.56
2778	118.09 ± 19.16	112.30 ± 56.71	108.68 ± 80.19	144.73 ± 24.68	118.32 ± 87.06
3869	39.44 ± 344.86	30.54 ± 240.27	49.32 ± 181.26	83.13 ± 75.06	90.65 ± 51.46
5385	40.75 ± 47.77	47.86 ± 6.30	53.51 ± 6.28	63.56 ± 6.32	65.31 ± 6.62
6597	44.87 ± 1.28	46.18 ± 1.20	47.09 ± 1.17	49.09 ± 1.21	51.73 ± 1.67
7685		52.52 ± 0.74	54.86 ± 0.94	56.75 ± 0.85	

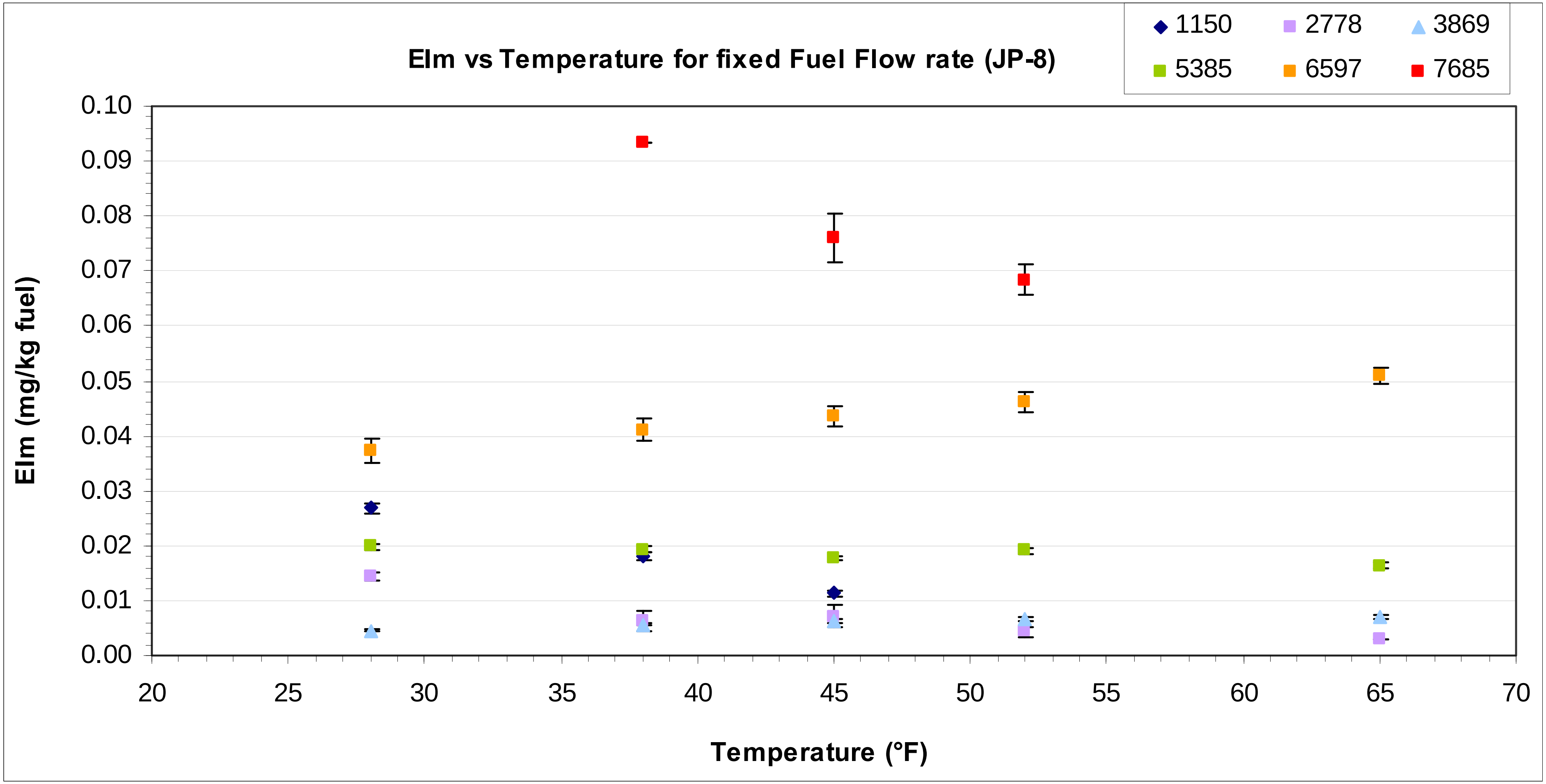
EIn (10^{14}/kg fuel)					
Fuel flow rate (lbs/hr)	Temperature (°F)				
	34	42	47	56	58
1150		0.173 ± 0.004	0.149 ± 0.003	0.107 ± 0.003	0.100 ± 0.003
2778	0.153 ± 0.007	0.115 ± 0.015	0.097 ± 0.010	0.066 ± 0.001	0.035 ± 0.001
3869	0.032 ± 0.001	0.066 ± 0.001	0.078 ± 0.002	0.100 ± 0.002	0.105 ± 0.003
5385	1.090 ± 0.010	0.777 ± 0.017	0.701 ± 0.015	0.564 ± 0.012	0.528 ± 0.012
6597	2.024 ± 0.018	2.028 ± 0.027	2.062 ± 0.032	2.109 ± 0.040	2.009 ± 0.033
7685		3.243 ± 0.029	3.477 ± 0.022	3.685 ± 0.030	

EIm (mg/kg fuel)					
Fuel flow rate (lbs/hr)	Temperature (°F)				
	34	42	47	56	58
1150		0.05 ± 0.10	0.06 ± 0.10	0.07 ± 0.10	0.07 ± 0.10
2778	1.59 ± 0.19	0.15 ± 0.11	0.18 ± 0.10	0.26 ± 0.09	0.13 ± 0.08
3869	0.02 ± 0.07	0.12 ± 0.21	0.14 ± 0.18	0.19 ± 0.12	0.20 ± 0.10
5385	1.07 ± 0.07	0.69 ± 0.08	0.67 ± 0.07	0.62 ± 0.06	0.63 ± 0.06
6597	3.10 ± 0.10	3.28 ± 0.11	3.51 ± 0.12	3.91 ± 0.14	3.81 ± 0.13
7685		7.46 ± 0.20	8.91 ± 0.26	10.15 ± 0.29	

Number-based emission index as function of temperature and fuel flow rate for JP-8



Mass-based emission index as function of temperature and fuel flow rate for JP-8



Define a temperature dependence metric:

- For a fixed fuel type, fuel flow rate, and aerosol parameter
- $Mcr_n = |ap_n(T_a) – ap_n(T_b)| / (\delta ap_n(T_a) + \delta ap_n(T_b))$
- $Mcr_n \geq 1$ ➔ Significant temperature effect
- Percent change
  $\Delta\% = 200*|ap_n(T_a) – ap_n(T_b)| / |ap_n(T_a) + ap_n(T_b)|$

Change in JP8 emissions due to temperature variation

ap	Fuel Flow rate (lbs/hr)	Mcr	Δ%
Dgn	1150	0.8	2
	2778	2.4	17
	3869	3.1	26
	5385	1.3	4
	6597	1.4	5
	7685	0.5	3
Dgm	1150		
	2778	0.6	21
	3869	3.9	28
	5385	3.2	7
	6597	2.7	5
	7685	1.3	2
EIn	1150		
	2778	11.9	22
	3869	17.4	48
	5385	6.6	29
	6597	3.3	20
	7685	8.5	42
EIm	1150	10.5	82
	2778	14.9	132
	3869	3.9	42
	5385	2.5	19
	6597	3.7	31
	7685	3.9	31

Change in FT1 emissions due to temperature variation

ap	Fuel Flow rate (lbs/hr)	Mcr	Δ%
Dgn	1150	2.1	34
	2778	1.8	27
	3869	1.2	35
	5385	1.1	5
	6597	2.2	9
	7685	1.8	6
Dgm	1150	0.5	19
	2778	0.6	28
	3869	0.2	99
	5385	1.4	46
	6597	2.3	14
	7685	2.6	8
EIn	1150	15.9	73
	2778	18.8	126
	3869	22.4	107
	5385	25.6	70
	6597	1.4	5
	7685	7.5	13
EIm	1150	1.2	141
	2778	5.4	171
	3869	1.02	165
	5385	3.4	52
	6597	3.4	23
	7685	5.5	31

Correlation between the temperature dependencies of JP8 and FT1 emissions

ap	Fuel Flow rate (lbs/hr)	CC
Dgn	1150	1
	2778	-0.93
	3869	-0.97
Dgm	5385	-0.58
	6597	0.33
	7685	1
EIn	2778	0.29
	3869	0.67
	5385	0.36
	6597	0.33
EIm	1150	0.89
	2778	0.57
	3869	0.98
	5385	0.83
	6597	0.98

Conclusions

- PM emission data collected over an ambient temperature range -2.2 to 18.3 C.
- Significant dependence on temperature was observed.
- Mcr's averaged
  - 4.9 JP8
  - 5.4 FT1
- Δ%'s averaged
  - 28 JP8
  - 54 FT1
- Correlation of T-dependence between fuels
  - No consistent correlation for Dgn and Dgm
  - Positive correlation for the EI's
  - Stronger correlation for EIm (correl. Coef. = 0.85)

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