ISABE-2007-1277

Gas Emissions Acquired during the Aircraft Particle Emission Experiment (APEX) Series

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Abstract

NASA, in collaboration with other US federal agencies, engine/airframe manufacturers, airlines, and airport authorities, recently sponsored a series of 3 ground-based field investigations to examine the particle and gas emissions from a variety of in-use commercial aircraft. Emissions parameters were measured at multiple engine power settings, ranging from idle to maximum thrust, in samples collected at 3 different down stream locations of the exhaust. Sampling rakes at nominally 1 meter down stream contained multiple probes to facilitate a study of the spatial variation of emissions across the engine exhaust plane. Emission indices measured at 1 m were in good agreement with the engine certification data as well as predictions provided by the engine company. However at low power settings, trace species emissions were observed to be highly dependent on ambient conditions and engine temperature.

Introduction

With concerns over the environmental effects [1 – 4] of aircraft exhaust, National Aeronautic and Space Administration (NASA) to sponsor a variety of studies in the past decade to gather detailed aircraft emission data in order to assess the environmental impact of aviation and to develop ultra efficient and low emissions turbine engine technology [5 - 9]. Important recent studies include a series of three ground-based field investigations to examine the particle and gas emissions from a variety of in-use commercial aircraft.

The first in the series was Aircraft Particle Emissions eXperiment (APEX) which was conducted at NASA Dryden Flight Research Center (DFRC) in April, 2004 using the NASA DC-8 aircraft with CFM56-2C1 engines. Three sampling probe stands were anchored at 1, 10, and 30 meters (m) downstream of the engine exit plane. Gas samples were drawn continuously from the 1 and 10 m probes. Figure 1 shows the sample stands behind the NASA DC-8 aircraft with CFM56-2C1 engines.

Jet Emissions Testing for Speciation (JETS)-APEX2 was conducted at Oakland Airport in August, 2005. Southwest Airlines provided four aircraft, two B737-7H4 with CFM56-7B22 engines, one B737-3H4 with CFM56-3B1 engines, and one B737-3Q8 with CFM56-3B2 engines. Four sampling stands were anchored at 1 m (both right and left engines), 30 m, and 50 m. Gas samples were drawn from 1m (both right and left) and 30 m probes. Figure 2 shows sample stands used in JETS-APEX2.

APEX3 was conducted at Cleveland Hopkins Airport in November, 2005. Continental Airlines provided four aircraft: two B737-3T0 with CFM56-3B1 engines and two B757-324 with RB211-535E4B engines. ExpressJet Airlines provided two aircraft: one ERJ-145XR with AE3007-A1E engines and one ERJ-145ER with AE3007-A1P engines. FedEx Corporation provided one aircraft, A300B4-622R with PW4158 engines. NASA Learjet25 with CJ610-8ATJ was also studied. Three sampling stands were anchored at three down stream locations: 1, 30, and 42 m for large engines and 1, 15, and 30 m for small engines. Figure 3 shows sample stand behind the FedEx A300-B4-622R aircraft with PW4168 engines.

These measurement campaigns brought researchers from federal laboratories, academic institutions, and private industry together to advance the knowledge of aircraft emissions and their initial evolution in ground atmosphere.

Objective

A suite of conventional gas analyzers was used to measure the major and minor gas-phase species emissions. The instrument suite and sampling system were tailored to provide emission parameters that are archived in the International Civil Aviation Organization (ICAO) database in order to confirm that the engine was operating within its certified emission limits; to map (using multi-port sampling rakes) the spatial distribution of emissions across the engine exhaust plume; to provide baseline plume information for interpreting the particle emission observations; and to provide the information necessary for calculating emission indices (EI). Gas emissions played a critical role in anchoring the engine performance and sample locations in the exhaust plume.

In this paper, the discussion focuses on the gas emissions acquired at 1 m behind the engine exit plane from all models of CFM56 engines available during these three measurement campaigns.

Experimental Setup

Fuel

Three different fuels were used during APEX to investigate the effect of fuel composition upon emissions: baseline JP8 fuel from Edwards Air Force Base; high-sulfur fuel created from baseline fuel doped with tertiary butyl disulfide (C12H18S2); and high aromatic Jet-A fuel purchased from a California refinery. There was no special arrangement for the fuels used in JETS-APEX2 and APEX3, fuels were what were left in the fuel tank with additional amount added from the airport fuel storage. Fuel and oil samples were collected in all three campaigns and detail analysis were done post-test.

Test Matrix

Two different test matrices were employed in APEX : (1) "NASA" matrix was designed to parametrically study the effects of engine operation parameters on exhaust emissions and including approximately 4 minutes sampling time at thrust levels of ground idle (approximately 4%), 5.5%, 7%, 15%, 30%, 40%, 60%, 65%, 70%, 85%, and 100% (actual maximum permitted was 93%). This series of engine power level was repeated once by lowering the power to ground idle before the next one. (2) "EPA" matrix was intended to simulate airport operations. It ran four repeated ICAO-defined Landing-Take-Off (LTO) cycles of 26 minutes at idle (7%), 0.7 minutes at takeoff (100%), 2.2 minutes at climb (85%), and 4 minutes at approach (30%).

JETS-APEX2 chose similar engine thrust level with a different way to repeat the thrust levels. The cycle was defined as ground idle (approximately 4%), 7%, 15%, 30%, 40%, 60%, 85%, and take-off (maximum thrust level permitted by local ambient conditions), 85%, 60%, 40%, 30%, 15%, 7%, ground idle.

APEX3 designed an extra step in the series: ground idle (approximately 4%), take-off (maximum thrust level permitted by local ambient conditions), 7%, 15%, 30%, 40%, 60%, 85%, take-off, ground idle, take-off, 85%, 60%, 40%, 30%, 15%, 7%, ground idle.

Sample Lines

Figure 4 shows a schematic of the gas sample system. Sample air was drawn through the sample inlet probes, 12.2 m of 9.5 mm stainless steel (SS) sample lines, the heated valve selection box (with computer-controlled valve operation to determine which probe of which rake the sample came from), heated boost pumps, another 18 m of 9.5 mm SS sample line, to the measurement systems. All sample lines and valve box were heated to 150oC with electric heater tape according to Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 1286B. The rake was cooled with water from an outdoor faucet to protect the o-rings that vacuum-sealed the inlet probes inside their mounting brackets. Because a high-pressure pump is required to force water through the narrow passages in the gas probes, we suspect that the cooling flow had a minimal effect on sample gas temperatures.

JETS-APEX2 sample lines were setup similarly to the APEX with 10 m sample line between probe and heated box and another 15 m to the measurement system. APEX3 sample lines were again setup similarly with 10 m sample line between probe and heated box and another 15 m to the measurement system.

1 m Sample Rake

In APEX, the 1 m stand held a sample rake that contained six gas probes and six particle probes that were alternatively positioned. It also supported six external, large-diameter gas probes to supply sample air to measurement systems that had high flow demands. A shroud was installed on the rake to protect the externally connected probes. (Figure 5) Thermocouples were attached to each external probe and temperatures were recorded.

In Jets-APEX2, both of the 1 m stands each held a sample rake the same as the APEX 1 m sample rake with similar probe orientation, but without external probes. There were three gas sample probes available for our use as indicated in Figure 6.

In consideration of wide range of aircraft included in APEX3, a new sample rake with a scissor-jack base that can adjust height and/or tilt the sample rake was specially designed. Water-cooling feature was decided not necessary for hardware survivability. Figure 7 shows that the rake contained eighteen gas and eighteen particle probes were installed alternatively, and neighboring 2 gas probes were paired to a common line connecting to the heated valve box, hence there were total 9 gas inlet positions. Nominally, there were three combined gas probes for NASA gas measurement system that were in the exhaust. Temperature and pressure were measured at the same location of gas probes.

Measurement Systems

Conventional gas analyzers (CGA) were used as the primary gas-measurement system, the CGA employed standard methods recommended by ICAO Annex 16 Volume 2 and SAE ARP1256B. It measured a variety of major and minor gas species including carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), total unburned hydrocarbon (THC), and nitrogen oxides (NO_X), which is the sum of nitric oxide (NO) and nitrogen dioxide (NO_2).

A flow diagram of gas sample flow and the analyzers is shown in Figure 8. Each analyzer had its own pump to control and meter the sample flow rate. An auxiliary heated pump could be added to the main sample line if the total sample flow rate was too low. A quality assurance plan was developed for the CGA system. Individual components of the CGA system were individually calibrated before the experiment, and then the entire system was calibrated again after installation was completed. The pre-campaign calibration procedures for the gas analyzers are stated in 40CFR 86 Subpart D. Different calibration procedures were given for the different detection methods used by the analyzers. The pre-test and post-test calibration procedures are stated in 40 CFR 86. They do not differentiate between analyzers.

Results

For any given thrust level, engine operation and gaseous emissions were influenced by ambient conditions. Although pressure was approximately constant throughout each campaign, ambient temperature varied by up to 20oC and significantly effected fuel flow rates to achieve the specific engine power setting. This phenomenon was evident from the spread of calculated fuel air ratio (FAR) and measured gas emissions at the same thrust level. Hence all data were plotted against fuel flow rate instead of thrust level.

Emissions variation caused by probe positions was studied in APEX. Figure 9 demonstrates clearly that although all six gas probes on the 1 m rake were within the core engine exhaust, some of the outer probes exhibited greater levels of variability than the others. In particular, samples collected from probes G5 and G6 were often observed to be diluted by 5 to 10% with fan air at low power conditions. However, their emission indices (EI's) were in reasonable agreement with other probes.

Fuel Air Ratio

Figure 10a shows sample FAR calculated from all measured data during APEX and from GEAE cycle calculations for CFM56-2C1 engine. Values from all six probe and three fuel types were within 10% of GEAE predictions. Figure 10b shows sample FAR calculated from measured data of CFM56-3B1 engines during JETS-APEX2 and APEX3. Values at each of the four LTO thrust levels were within 10% of the expected value with the exception of one aircraft (tail number N70330). This was caused by probes located at the outer edge of exhaust flow, i.e. diluted by fan and ambient air. Figure 10c shows similar agreements of 10% for the CFM56-3B2 engine from JETS-APEX2 with exception of one probe which was diluted by fan and ambient air. Figure 10d shows agreement within 5% for the CFM56-7B22 engine from JETS-APEX2.

Nitrogen Oxides NO_x

Nitrogen oxides (NO_x) include both nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Emission index of nitrogen oxide ($EINO_x$) were corrected for humidity to the standard atmospheric condition (0.00629 kg-water/kg-dry air) then plotted against ICAO LTO data.

Figure 11a shows the measured $EINO_x$ of CFM56-2C1 engine from APEX in good agreement, i.e. within 10%, with both ICAO data and GEAE prediction. The spread of the data are minimized to within 2 - 3 % when normalized to combustor inlet temperature. Figures 11b, 11c, and 11d respectively show similar 10% agreement with each engine model's certification data recorded in ICAO database. $EINO_x$ appeared to show no noticeable dependency on fuel types or probe locations.

Carbon Monoxide CO

As shown in Figure 12a, the measured EICO of CFM56-2C1 engine from APEX were in excellent agreement, approximately 2 - 3% with ICAO data as well as with GEAE predictions. Figures 12b, 12c, and 12d show similar agreement with ICAO data. EICO increased exponentially at low thrust level. There were significant differences between idle (7% engine thrust) and ground idle (~4% engine thrust) which could be of more concerns for airport air quality.

EICO has a negative correlation with $EINO_x$, i.e. EICO increases when $EINO_x$ decreases, as shown in Figure 13. Because combustors are typically designed to operate most efficiently at high thrust levels, it is a well established fact that EICO is highest at the lowest power conditions. On the other hand, $EINO_x$ was typically a maximum at takeoff power because the combustor flame temperature peaked under these conditions.

Unburned Hydrocarbon HC (UHC or THC)

Because CO and the HC are formed by similar reaction chemistry within the combustor, EIHC exhibited the same trend as EICO. However, concentrations of unburned hydrocarbon were significantly more sensitive to engine operating temperature than CO as is readily apparent in Figures 14a, 14b, 14c, and 14d.

In addition, HC emission levels were higher when the engine was cold (during the initial run up). This was a consistent finding throughout the 3 campaigns, but most evident in APEX because NASA DC-8 aircraft was dedicated to the test unlike other aircraft typically came soon after a commercial flight. Similar effects were noted in GEAE's early emissions variability testing of the CF6-50 [10]. It is understood that certification data were typically acquired on warm engines.

Figure 15 demonstrates that EIHC from APEX are at the highest values at engine cold-start and decrease with time for the same power conditions (with warmer engine). This phenomenon can be observed more clearly when EIHC data are grouped by cold and warm engine conditions as shown in Figure 16.

Conclusion

Gas emissions measured in samples drawn from multiple probe tips on 1 m sample rake provided information on the engine operation and exhaust plume characteristics that was essential for interpreting simultaneous particle emission measurements. Overall, engine operation seemed to be normal.

Gas emissions, $EINO_X$, EICO, and EIHC, agreed very well with the ICAO database and the expected values for each engine type. EIs for the major and minor species (CO, CO_2, NO, NO_X) were not dependent upon fuel type, but THC and CO emissions were highly sensitive to variations in ambient temperature.

Reference

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[6] Wey, C. C., et al., "Engine Gaseous, Aerosol Precursor and Particulate at Simulated Flight Altitude Conditions," NASA TM 1998-208509 and ARL-TR-1804, 1998

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[8] Anderson, B.E., "An overview of the NASA Experiment to Characterize Aircraft Volatile Aerosol and Trace-Species Emissions (EXCAVATE)," NASA/TM-2005-19019, 2005

[9] Wey, C. C., et al., "Aircraft Particle Emissions eXperiment (APEX)", NASA TM 2006-214382 and ARL-TR-3903, 2006

[10] Dodds, W. J. "APEX Engine Operation" http://particles.grc.nasa.gov APEX Conference Presentation, 2004

Figure 1: Photos of APEX sample stands - 1 m and 10 m stands each with a multi-probe rake, 30 m stand with a single probe

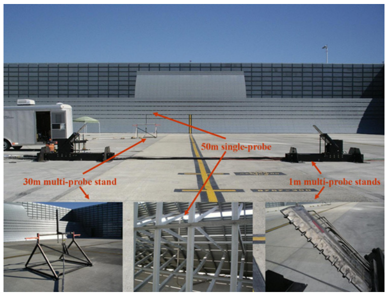

Figure 2: Photos of JETS-APEX2 sample stands - 1 m stands each with a multi-probe rake, 30 m and 50 m each with a single probe

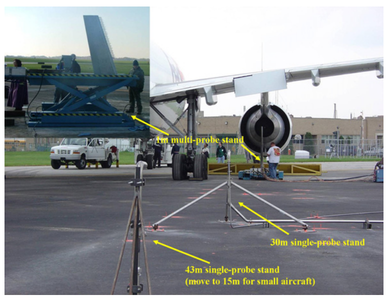

Figure 3: Photos of APEX3 sample stands - 1 m stand with a multi-probe rake and 30 m and 43 m stands each a single probe

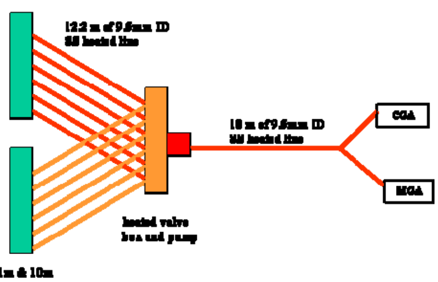

Figure 4: Schematic of sample system showing 6 gas probes connected to a heated switch box that allows sampling from any chosen

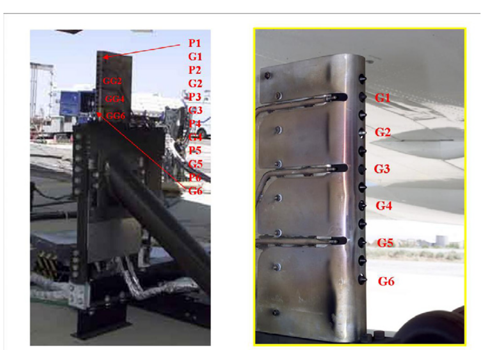

Figure 5: Photos of 1 m rake with 6 gas, 6 particles, and 6 external probes used in APEX

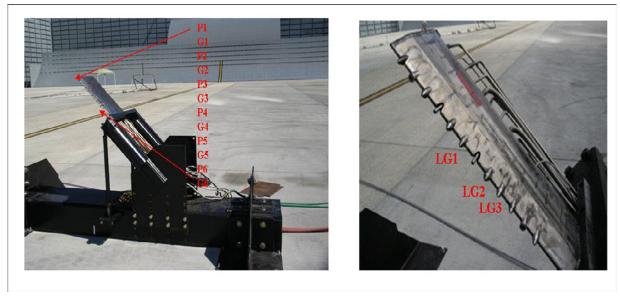

Figure 6: Photos of 1 m left rake with 6 gas and 6 particle probes used in JETS-APEX2; 3 of gas probes are for NASA gas measurement system

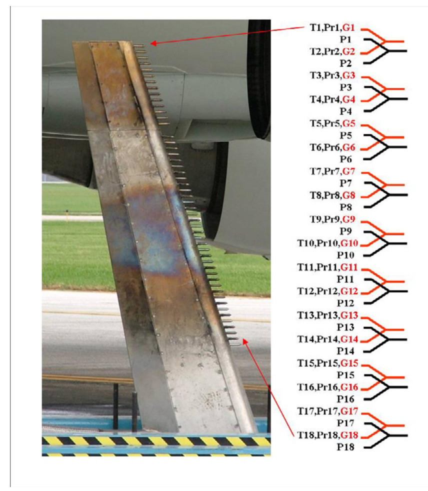

Figure 7: Photo of 1 m rake with 9 combined gas probes, 9 combined particle probes, and 18 thermal couples and pressure transducers used in APEX3

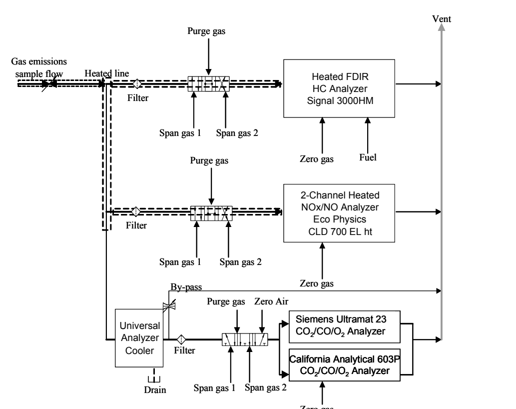

Figure 8: Schematic of gas measurement system with NO/NO_X, $CO/CO_2/O_2$, and THC analyzers with sample and calibration gas line

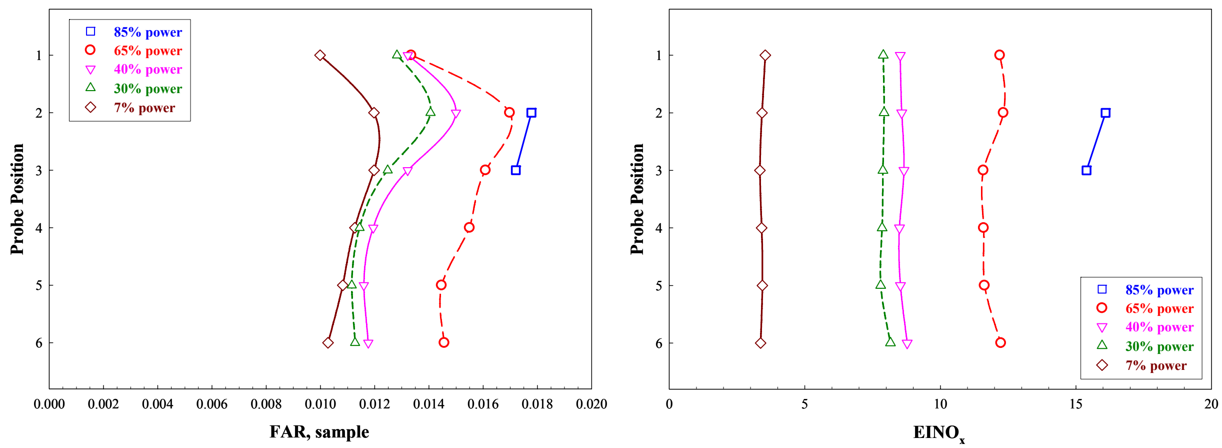

Figure 9: (a) $EINO_X$ (b) FAR vs. APEX 1m rake probe positions at several engine thrust levels

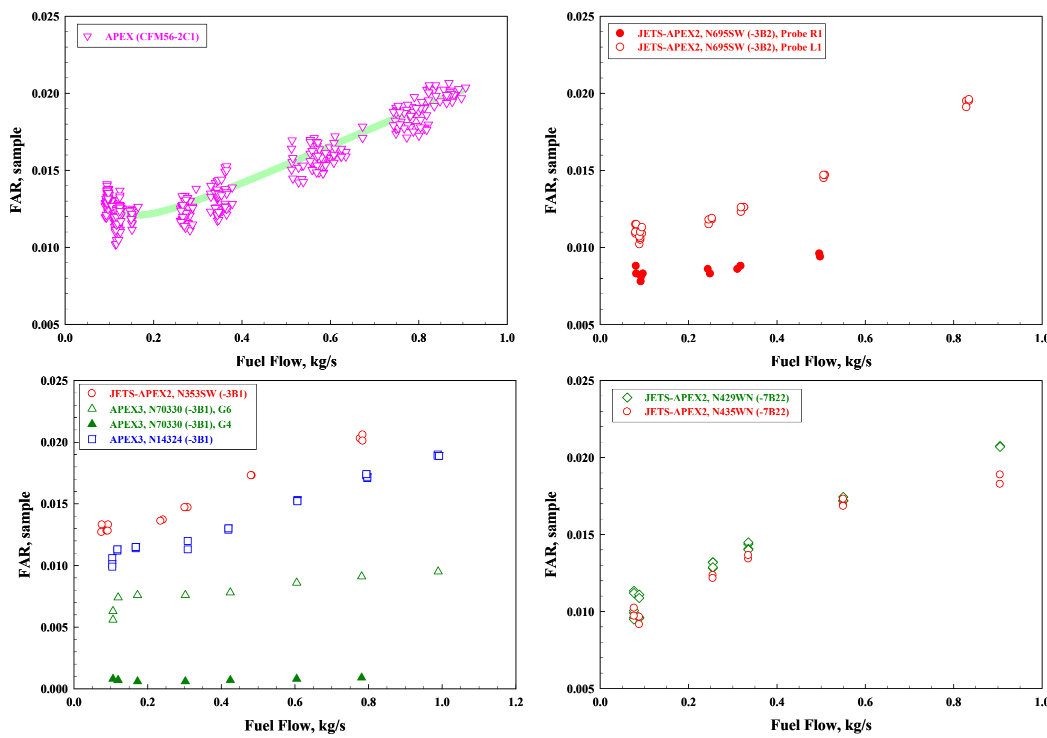

Figure 10: FAR vs. engine fuel flow rate (a) CFM56-2C1 (b) CFM56-3B1 (c) CFM56-3B2 (d) CFM56-7B22

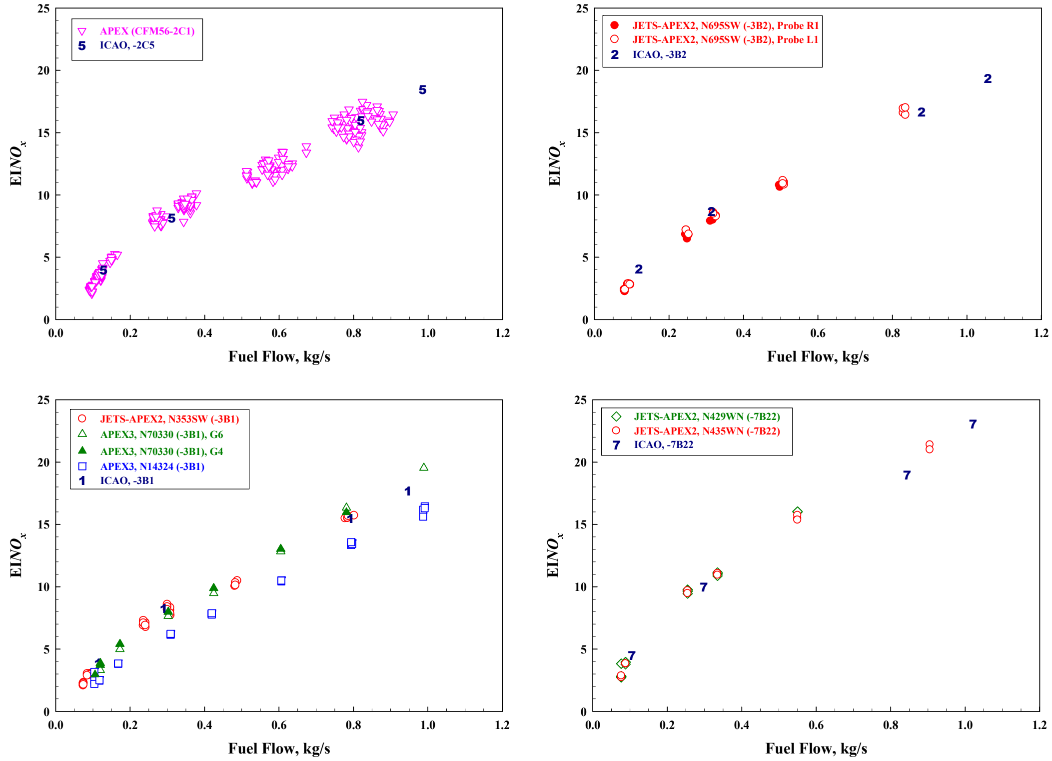

Figure 11: $EINO_X$ vs. engine fuel flow rate (a) CFM56-2C1 (b) CFM56-3B1 (c) CFM56-3B2 (d) CFM56-7B22

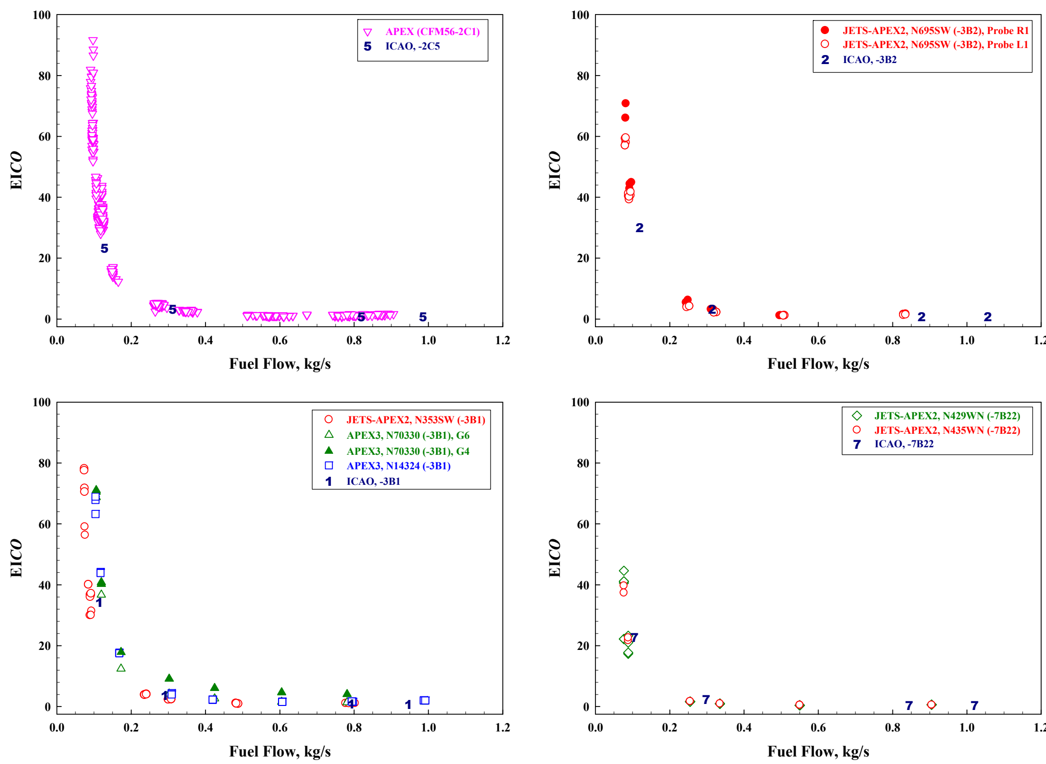

Figure 12: EICO vs. engine fuel flow rate (a) CFM56-2C1 (b) CFM56-3B1 (c) CFM56-3B2 (d) CFM56-7B22

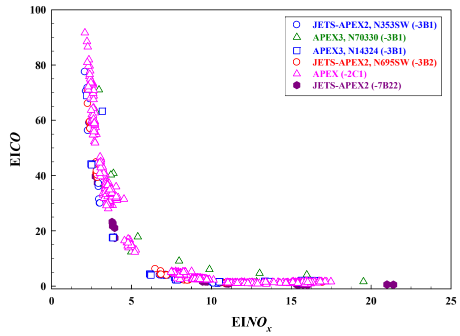

Figure 13: EICO vs. EINO$_x$

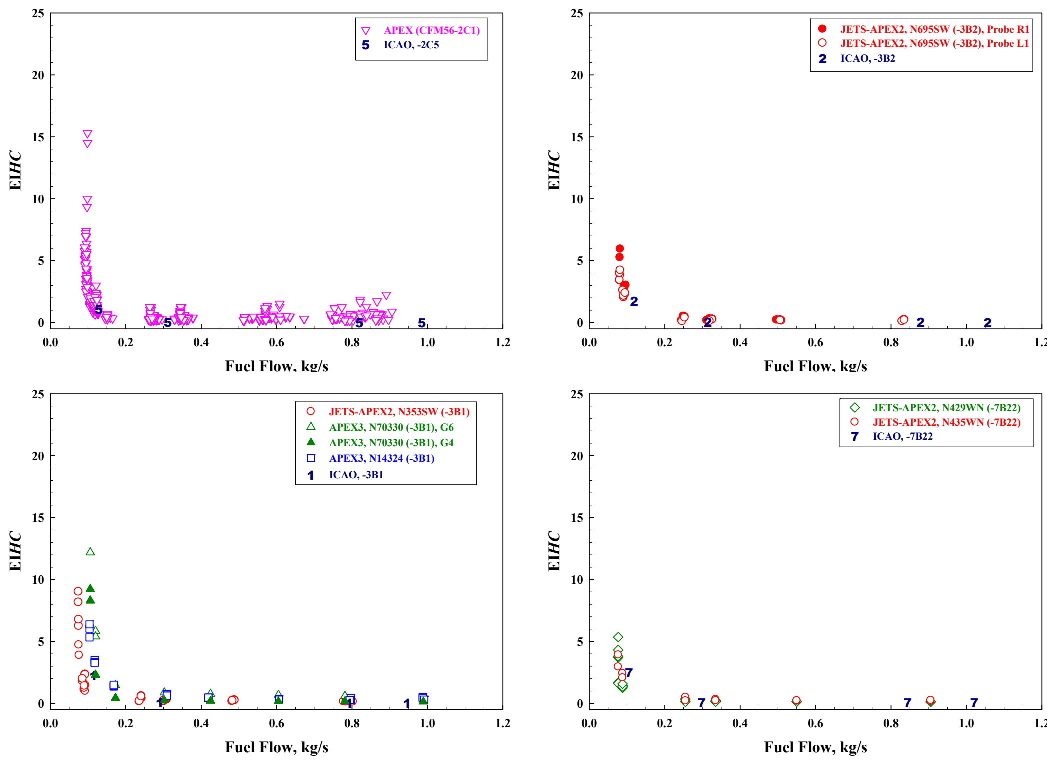

Figure 14: EIHC vs. engine fuel flow rate (a) CFM56-2C1 (b) CFM56-3B1 (c) CFM56-3B2 (d) CFM56-7B22

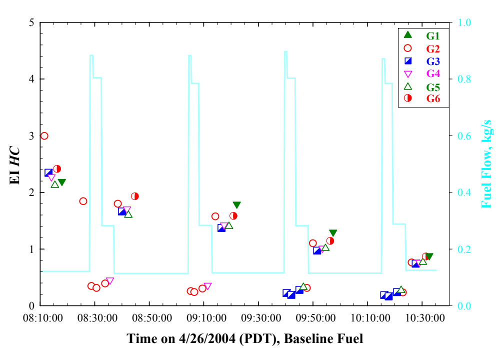

Figure 15: EIHC from individual probes during APEX with baseline fuel

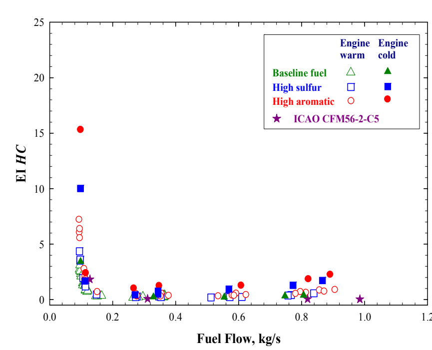

Figure 16: Effect of engine temperature on EIHC