Project 024B PM Emission Database Compilation, Analysis and Predictive Assessment

The Pennsylvania State University, GE U.S. Aviation

Project Lead Investigator

Randy L. Vander Wal
Professor, Energy and Mineral Engineering, Materials Science and Engineering
John and Willie Leone Family Dept. of Energy and Mineral Engineering
Penn State University
104 Hosler Bldg.
814-865-5813
ruv12@psu.edu

University Participants

Penn State University

- P.I.(s): Randy L. Vander Wal, Professor, Energy and Mineral Engineering, Materials Science and Engineering
- FAA Award Number: Grant 11895155, Amendment No. 011, under 13-C-AJFE-PSU.
- Period of Performance: Aug. 18th, 2014, Sept. 30th, 2016
- Task(s):
    1. Develop Database. Include mass and number nvPM emission data for fuels, engine, measurement method(s) and engine conditions.
    2. a) Compare current ground nvPM predictive methods to measured values from NASA campaigns.
       b) Compare current cruise scaling approximation to measured cruise values from NASA's ACCESS
    3. Correct current engine condition predictive methods using proprietary GE cycle deck data
    4. Compare current methods using accurate engine condition inputs
    5. Formulate new predictive relationships for nvPM with engine thrust level.
    6. Evaluate whether a universal relation or separate ones are required for Jet-A and alternative fuels.
    7. Evaluate whether a universal relation or separate ones are required for Jet-A and alternative fuels.

Project Funding Level

FAA funding: $149,975.

GE Aviation, U.S. is the Industrial Partner supplying matching funds, level $150,000, with $1,724895 available to the FAA COE AJFE ASCENT program, administered through Washington State University.

Investigation Team

Professor Randy L. Vander Wal, Penn State EME Dept., with responsibilities for project management, reports, interfacing with FAA program manager, and mentoring the graduate student supported on this project.
Joseph P. Abrahamson, Graduate student. Responsibilities include data assembly, analysis and predictive relation assessment, towards completion of a Ph.D. program.

Project Overview

Relationships between fuel components, engine operating conditions and emissions are necessary towards understanding their formation and achieving mitigation. Present synthetic paraffinic kerosene (SPK) aviation fuels differ from petroleum derived aviation kerosene by their high paraffin (~ 53% n-paraffin, 47%, iso-paraffin, FT Shell), napthene content (~ 87% cycloparaffin, 12%, iso-paraffin, FT Sasol), but most notably absence of aromatics (< 0.5%) and negligible organo-sulfur compounds. Future alternative fuels may have substantially higher cycloparaffin content while hydrotreated depolymerized cellulosic jet (HDCJ) fuel may even (re)-introduce aromatics, adding to composition variability and need for understanding emissions from varied components and their mixtures.

The emerging use of alternative fuels with varied compositions markedly changes the non-volatile PM (nvPM) emissions. Both number density and mass changes are found, and hence emission index (EI). These measures in particular are relevant to potential regulations. These quantities can vary with engine power, and are strongly dependent upon fuel components, namely paraffin, naphthene and aromatic content. The value of these studies is that assembling data across field campaigns, fuels and measurement methods will build a comprehensive picture of PM emissions dependence upon fuel components, engine type, power level and minor fuel species such as sulfur.

Objective(s)

Nonvolatile PM emissions from aircraft engines are primarily comprised of soot particles formed in the engine combustor. The amount of soot formed within a specific combustor design can change by more than an order of magnitude as engine thrust increases from idle to takeoff, due to increasing combustor pressure, temperature, and fuel-air ratio. In order to understand the influence of fuel properties on nvPM emissions from a specific engine, it is important to separate fuel effects from changes in emissions due to differences in combustor operating conditions, which are affected by engine thrust level, ambient conditions, altitude, flight Mach number, and engine deterioration.

Research Approach

Emerging use of alternative fuels markedly changes non-volatile PM (nvPM) emissions. Substantial numbers and mass changes are observed. Number and mass measures in particular are relevant to future regulations. These quantities can vary with engine power, and are strongly dependent upon fuel components, namely paraffin, naphthene and aromatic content. Presently only a mass-based emission index (EI) is used, but has significant uncertainty given its present derivation by smoke number.

In light of this situation nvPM emissions data from the FAA CLEEN program, NASA-led ACCESS campaigns, and related NASA Aviation Particle Emission Experiment (APEX) I, and Alternative Aviation Fuel(s) Experiment (AAFEX) I & II campaigns has been collected. These campaigns and tests investigated alternative fuels, varied fuel components and assessed the role and aromatics. To-date there is no comparison(s) between these studies or compilation of results into a unified database. The value of these studies is that assembling data conducted using one engine class, (representative of rich-dome style combustors), across a range of fuels and measurement methods will build a comprehensive picture of PM emissions dependence upon fuel composition and engine thrust at ground and cruise.

Previous studies have used simplified relationships to estimate emissions as a function of engine operating conditions. A more detailed two-step process is planned to correct for these effects in this proposed study. GE Aviation has detailed proprietary analytical models for each GE and CFMI engine type to predict pressures and temperatures throughout the engine as a function of thrust and inlet conditions. The first step in the study is to use this type of model to calculate combustor inlet pressure, temperature, and fuel-air ratio at operating points where nvPM emissions have been measured, and re-evaluate current predictive methods using correct engine operating conditions. By comparison to ground and cruise nvPM emission data, deficiencies in current predictive tools can be identified and new predictive relations can be developed. With relations benchmarked against measurements, and confidence in engine operating conditions as inputs, measured nvPM from alternative fuels may be used to guide expansion of these new predictive relations so as to encompass alternative fuels. Thereafter these relations will be assessed by comparison to nvPM test data from other engines such as from NASA studies and the FAA CLEEN program.

Milestone(s)

Milestones accomplished include the following.

1. Database development for nvPM mass, number emission data for fuels and engine thrusts, across field campaigns.
2. GE Aviation cycle deck calculations at ground and cruise conditions, matching test point conditions in the NASA ACCESS field campaign.
3. Comparison and evaluation of current predictive methods to ground and cruise measurements using accurate engine operating conditions.

Major Accomplishments

Analysis of current predictive relations for assessing PM emissions by comparison to both ground and cruise data for JP-8 fuel, using accurate engine operating conditions, courtesy of our partner, GE Aviation's engine cycle deck calculations.

Benefits: Predictive tools, even if semi-empirical in nature but validated against alternative fuels, blends and few-component surrogates would have tremendous value in evaluating future fuels without requirement of expensive rig or full-scale combustor testing.

Publications
COE AJFE ASCENT Quarterly Reports, thus far.

- Abrahamson, Joseph. Aviation Black Carbon Mass Predictive Model for Alternative and Conventional Fuels at Ground and Cruise, 2016. https://ascent.aero/wp-content/uploads/sites/192/2015/12/Hartman_CH_7-20-16JPA.pdf
- Speth R.L., Rojo C., Malina, R. and Barrett S.R.H., "Black carbon emissions reductions from combustion of alternative jet fuels." Atmospheric Environment 105, pp. 37-42, 2015. DOI:10.1016/j.atmosenv.2015.01.040

Outreach Efforts
Presentations on project 24B status at the FAA COE AJFE ASCENT meetings, Oct. 2014, March 2015.

Presentation on project 24B results to the Aviation Emissions Council (AEC) Annual Roadmap Meeting, May 2015.

Presentation on project 24B results on the AEC monthly telecon, Sept. 2015.

Awards
Joseph P. Abrahamson – EME (Energy and Mineral Engineering Dept.) The Robert and Leslie Griffin Award in Fuel Science, 2014.

Student Involvement
The current graduate student, Joseph P. Abrahamson, is conducting data assembly, analyses and predictive relation assessment, towards partial fulfillment of his Ph.D. program in EME, with Fuel Science option.

Plans for Next Period
To maintain the same numbering of tasks for this project are listed according to the prior section, with description following.

4. Formulate new predictive relationships for nvPM with engine thrust level.
   A kinetically based relation incorporating both formation and oxidation rates will be applied with input parameters including combustor temperature, fuel/air ratio and compressor inlet pressure.

5. Evaluate whether a universal relation or separate ones are required for Jet-A and alternative fuels.
   Using test data from NASA led field campaigns, including ground and the recent ACCESS campaign that included cruise, our new relation will be expanded so as to account for alternative fuels with varied components, in particular an absence of aromatics and overall higher H/C content.

6. Evaluate whether a universal relation or separate ones are required for Jet-A and alternative fuels.
   The accuracy of the new predictive relation will be the criteria by which to have one universal relation for both ground and cruise, or, separate ones.