Preliminary Investigations of Fuel Cloud Formation in Fuel Tank Ullage

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Fuel Tank Test Cell
Description of Project:

- Simulate realistic tank dynamics in fuel tank cloud chamber:
  - Preflight scenario - fuel tank is heated on bottom and cooled on top.
  - Takeoff scenario - fuel tank is heated before take-off and then cooled while climbing
- Identify conditions that promote droplet formation in fuel tanks
- Understand vapor dynamics to prevent/minimize explosive conditions
Benefit:

- Supplement to FAA tank inerting program
  - Identify “dynamic” flammability limits
  - Improve reliability of fuel tank explosion risk analysis
Background: Static (Equilibrium) Flammability

- Flammability envelope of fuel tank ullage depends on ignition limits, [Jet A] and [O₂]
  - [O₂] depends on altitude and temp.
    - Air composition invariant in troposphere and stratosphere
    - Air density varies with altitude
  - [Jet A] depends on temp. and loading
    - Saturation pressure limits the concentration
    - Loading influences Psat(T)
Background: Dynamic (Non-Equilibrium) Flammability

- Flammability outside the static flammability envelope

**CASE 1**: High-volatility fuels may be flammable beyond the rich limit because of aspiration

**CASE 2**: Low-volatility fuels may be flammable below the lean limit if suspended droplets are present in the ullage
Background: Dynamic Flammability (Cont.)

When droplets of sufficient size and number density are present, fuel tank ullage at any lean fuel-vapor/air ratio can be flammable, even in an atmosphere without any premixed fuel vapor (Burgoyne and Cohen, 1954; Ott, 1970). Two distinct dynamic conditions occurring in aircraft fuel systems can result in the formation of fuel mists (Ott, 1970):

• sloshing and vibration (agitation)
• pressure changes (homogeneous, gas-phase condensation)

Nester (1967) and Ott (1970) investigated agitation

• While fuel droplets can significantly lower the lean limit, aircraft just don’t get that agitated

No one has investigated homogeneous, gas-phase condensation
Progress to Date:

- Reconciled Discrepancies
- Construction of the Fuel Tank Test Cell
- Installation of the Test Facility
- Shakedown Runs
- Acquisition of Droplet Diagnostic Equipment
- Program of Experimental Investigation
Progress to Date (cont.): Test Cell Construction

- Preliminary drawings (L. Morton – 10/10/00)
- Boeing-Seattle funding, $30,000
- FEM/Design review (T. Briscoe – 11/3/00)
  - Design Pressure of 10 psi vac
  - Structural design per OSHA Standard 29 CFR, part 1926.152 (API Std. No. 620)
  - Finite Element Model to determine loads in stiffener tubing around windows
- Blueprints (Boeing – 11/15/00)
- Test cell fabrication (Boeing – 2/28/01)
- Test cell delivery (3/15/01)

Test Cell Design
- Optical access via LEXAN windows
- 7’ x 3.5’ x 3.5’ (~ 85 cu. ft. or 640 gal.)
Progress to Date (Cont.): Test Facility Installation

- Laboratory facilities modifications
- Eductor pump system
- Heating-cooling system
- Design computer control system
- Installation/calibration
Progress to Date (Cont.): Test Facility Installation (Cont.)

- **Laboratory facilities**
  - Electrical
  - Ventilation

- **Eductor pump system**
  - Water-Jet w/control valve
  - dP/dt max., 5 psi/min
  - Design → 1000 ft/min climb
  - Problems with reservoir temp

- **Computer control system**
  - Tank pressure control
  - Surface temperature control
  - Data logging
Progress to Date (Cont.): Test Facility Installation (Cont.)

• Heating-Cooling system
  - Two 18 kW/3 ton heater/chillers
  - Design → 1000 ft/min climb
  - Manufacturer shipped with wrong PID temp. controllers
  - Heat exchanger problems
Progress to Date (Cont.): Shakedown Runs

- **Pressure Control System**
  - Water circulated through jet ejector (constant vacuum, $P_{\text{sat}}$ at $T_{\text{water}}$)
  - $dP/dt$ in tank regulated by control valve
  - 4 to 20ma controller adjusts control valve set point
  - Pressure transducers and 4 to 20ma controller connected to PC
  - Closed loop control

- **Results of Calibration/Shakedown**
Progress to Date (Cont.): Shakedown Results

Tank Temperature and Pressure History with Control Valve Fully Open

Tank Temperature and Pressure History with Control Valve Partially Closed

Time (minutes)

Pressure (torr) or Temperature (°F)
Progress to Date (Cont.): Shakedown Results

Control Valve Calibrations →

- Temperature drop during tank decompression due to adiabatic cooling
- $\Delta T$ correlates with $\frac{dP}{dt}$ (control valve setting)
Progress to Date (Cont.): Shakedown Results

- **Droplet formation via thermal diffusion configuration (1st Exp.)**
  - Tank bottom heated, top cooled
  - Thermal diffusion cloud chamber
  - Conditions:
    - Argon atmosphere
    - 10 gal. Jet A (1.6% mass loading)
    - Tank top 50 F
    - Fuel 90 – 110 F
  - Droplets 1st observed at 90 F (fuel)
Progress to Date (Cont.): Shakedown Results

P1: tank pressure (vac torr)
P2: tank pressure (torr)
TC01: internal tank temp. (-28 in.)
TC02: internal tank temp. (-20 in.)
TC03: internal tank temp. (-12 in.)
TC04: internal tank temp. (-4 in.)
TC05: tank side surface temp.
TC06: tank side surface temp.
TC07: tank top surface temp.
TC08: fuel pan temp.
Progress to Date (Cont.): Shakedown Results
Progress to Date (Cont.): Acquisition of Droplet Diagnostic Equipment

- Additional Funding via 2nd FAA Grant
  - Droplet sizing interferometry (2-D PDPA)

- Bring in Vendors to demonstrate
  - Video-based microscopic imaging
    - Theoretically capable of droplet characterization and velocity measurement
    - Long range microscopy is iffy
  - Mie scattering theory-based Fraunhofer diffraction technique (Malvern analyzer)
    - Relatively inexpensive
    - Line of sight averages on droplet size only
Progress to Date (Cont.): Program of Experimental Investigation

- Homogeneous condensation during tank decompression
  - Diabatic decompression during ascent
  - Experiments matching flight profile T, P-data

- Homogeneous condensation through thermal diffusion
  - Tank bottom heated, tank top cooled to match ground operations
  - Thermal diffusion cloud chamber

- Chemical composition of fuel, fuel vapor and droplets

- Competitive processes due to tank dynamics
  - Convective flow due to venting
  - Buoyant flow due to non-uniform wall temperatures
Concluding Remarks

- **Working Test Facility**
- **Some facility enhancements needed**
  - Heater/chillers and heat exchangers
  - Data acquisition hardware
  - PDPA
- **Investigation of homogeneous condensation underway**
  - Limit identification
  - Simulation of realistic preflight and in-flight conditions