Modeling Wing Tank Flammability

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Motivation

- Numerous accounts of wing tank explosions across the world
- Current flammability models are for center wing tanks
- The proposed regulation for wing tank safety are mostly based on center wing tank models
- Models will predict ullage concentrations existing during typical ground and flight operations
Current Work

- Flammable mixtures can be achieved in the wing tank
- Experiments are being conducted to build flammability models for wing tanks
- Current work involves
  - Predicting the influence of the surrounding temperatures on the characteristic fuel surface temperature
  - Creating a model that will predict flammability in wing tanks using heat transfer correlations
Overview

- Single Thermocouple Method (STM)
- Difference between Center Wing Tank and Wing Tank
- Center Wing Tank Flammability Model
- Heat and Mass Transfer Correlations
- Experimental Results
- Computational Results
Jet fuel is a mixture of many different hydrocarbons.

Fuel composition is characterized by the number of alkane reference hydrocarbons.

The approach reduces the number of components from over 300 down to 16 species (C5-C20 alkanes).

Liquid compositions of different JP-8 samples with varying flashpoints are presented in terms of the mole fractions of C5-C20 alkanes.
Single Thermocouple Method

Uses Fuel Air Ratio (FAR) calculator by Ivor Thomas

- Calculates fuel air ratio over a range of altitudes and temperatures
- All compounds with same carbon number were assigned together
- Fuel is segregated based on boiling points of alkane species respective of their carbon number
Single Thermocouple Method

At constant temperature, the THC increases as the pressure decreases.

Polynomial correlation between Scaled THC and temperature.

Film temperature is calculated at a given pressure and THC.
Center Wing Tank (CWT)

- The CWT has thin layer of fuel at the bottom of the tank
- 30% Mass Loading
- The tank is heated from the bottom due to heat released from underneath the tank
Wing Tank (WT)

- The WT is mostly filled with fuel
- 80% Mass Loading
- The tank is heated from the top from an ambient heat source such as the Sun
Sorting Data

- The data is sorted because of the difference in the driving force

- The data is sorted into
  - Ascending Profile
    - The top surface is hotter than the fuel surface
    - The ullage temperature governs the film temperature
  - Descending Profile
    - The fuel is hotter than the top surface
    - The fuel temperature governs the film temperature
Correlations

- Ascending profile
- Correlations between ullage temperature and fuel temperature
- Ullage temperature is greater than liquid fuel temperature
- Correlation coefficient 0.89
Correlations

- Ascending profile
- Correlating ullage temperature with film temperature
- Liquid fuel temperature is greater than ullage temperature
- Correlation coefficient 0.976
Correlations between ullage temperature and fuel temperature

Ullage temperature is greater than liquid fuel temperature

Correlation coefficient 0.41

Descending profile
Correlations

- Descending profile
- Correlations between ullage temperature and fuel temperature
- Liquid fuel temperature is greater than ullage temperature
- Correlation coefficient 0.93

Correlations of Ullage Temperature with Film Temperature
Summary of STM

- Correlation works best when:
  - Liquid fuel temperature is larger than the ullage temperature
    - Fuel temperature is the driving force
  - During Ascending pressure profile
    - Vapor pressure remains constant
Base Model

- Current CWT Model (Polymeropoulos 2004)*

- Natural convection flow field between the heated floor and the unheated ceiling and sidewalls

- Ullage gases are well mixed due to natural convection and mass transfer
  - Liquid vaporization
  - Vapor Condensation

- Natural convection flow is in the turbulent regime

* JET A VAPORIZATION IN A SIMULATED AIRCRAFT FUEL TANK, Polymeropoulos and Ochs 2004
Principal Assumptions

- Well mixed gas and liquid phases
  - Buoyancy induced mixing

- Quasi-steady transport using heat transfer correlations

- The analogy between heat and mass transfer for estimating film coefficients for heat and mass transfer

- The liquid fuel and wall temperatures are known from experiments
Computational Method

- **Inputs**
  - The tank geometry
  - Fuel loading
  - Liquid fuel composition
  - Tank pressure
  - Liquid fuel, and tank wall temperatures as functions of time

- **Computes**
  - Equilibrium species concentrations of Jet A in a uniform temperature, constant pressure tank
  - Temporal variation of vapor temperature and species concentration
CWT Model

- Simulation using center wing tank flight test data
- The calculated THC is in good agreement with the measured THC
CWT Correlations

- Heat & Mass Transfer Correlations
  - Horizontal surface:
    - Top surface: Lower surface of cooled plate
    - Top of Fuel Layer: Upper Surface of heated plate
  - Vertical Surface:
    - Laminar Forced Convection on a flat plate
Difference in Model Correlations

- The CWT model differs from the WT model in the ascending and cruise conditions due to:
  - Percent load
  - Ullage height
  - Heat and mass transfer correlations
  - Heat source
  - Surface being heated
Experiments

- Experiments were conducted
  - For 60% and 80% mass loadings
  - For equilibrium temperatures from 80°F to 100°F
  - For cruising altitudes of 25000 feet and 34000 feet
Experimental Equipment

- Experiments conducted in an altitude chamber
- Designed to simulate temperature and pressure similar to a flight profile
  - Can simulate altitudes from sea level to 100,000 feet
  - Can simulate temperatures from -100°F to +250°F
- NDIR gas analyzer used to measure the total hydrocarbon concentration
Experimental Setup

- An aluminum fuel tank of dimensions 24”w x 24” d x 36” h was used.
- Access panels on top for thermocouple penetration, ullage sampling, vent, and the fill tube.
- Thermocouples measured surface, ullage, fuel surface and bulk fuel temperatures.
- The vent was equipped with a mass flow meter.
Flight Profile

The following flight profile will be used in the altitude chamber:

- Cruise at 35000 feet
- Total flight time is 2.5 hours
Combination of Models

CWT model with WT dimensions

- Simulation using flight test data
- Using wing tank dimensions on a CWT flammability model
- Shows that the CWT model works for wing tanks in descending pressure profiles
Wing Tank Correlations

- Heat & Mass Transfer correlations
  - Horizontal surface: (Ascending)
    - Top surface: Laminar Forced Convection on a flat plate
    - Top of Fuel Layer: Laminar Forced Convection on a flat plate
  - Horizontal Surface (Cruise and Descending)
    - Top surface: Turbulent Forced Convection on a flat plate
    - Top of Fuel Layer: Laminar Forced Convection on a flat plate
  - Vertical Surface:
    - Laminar Forced Convection on a flat plate
Test Results

Ascending Top Surface Heat Transfer Correlations
Test Results

Cruise and Descending Top Surface Heat Transfer Correlations
Summary of Experimental Results

- Laminar Forced Convection during ascent
- Turbulent Forced Convection the rest of the flight
- Shows ullage gases are well mixed in the ullage
- High Reynolds number in the heat transfer cells in the ullage
Conclusion

- Single Thermocouple method can calculate THC using data from a single thermocouple in the tank
- The differences between the WT model and the CWT model:
  - Percent Load
  - Ullage Height
  - Heat and mass transfer correlations
  - Heat Source
  - Surface being heated
- The CWT model cannot be applied in the ascending and cruise profiles, but can be applied in the descending profiles
- Experiments will be conducted
  - To confirm the state of the ullage
  - To compare computed data to experimental data
Questions?