“Role of Alternative Aviation Fuels on Reducing the Carbon Footprint”

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Outline

- Role of alternative aviation fuels
- Introduction
- Collaborative research
- Fuels
- Research at MSTF-TAMUQ
- Takeaways
- Future directions
Aviation Alternative Fuels

- Need for alternative fuels?
  - Diversification / supply security
  - Reduce environmental impact

- Alternative fuels sources?
  - F-T based synthetic fuels (XTL)
    - X- Coal, Gas, Bio
  - Hydroprocessed Renewable Jet Fuel (HRJ) / Hydroprocessed-Ester / Fatty acids (HEFA) – from vegetable oils / animal fats
    - Camelina, Jatropa, Algae, Tallow, used cooking oil etc.,
  - Direct-Sugar-to-Hydrocarbon
  - Alcohols-to-Jet (ATJ)
Aviation Alternative Fuels

Developments / Milestones?

Source: www.icao.int

“A total of 21 airlines have now used alternative fuel for commercial flight. This is extremely impressive when just 5 or 6 years ago the entire concept was labeled as hypothetical.” - IATA report on Alternative Fuels, 9th Ed., Dec’ 2014

Key challenges in developments?

- Safety & Environmental impact
- Sustainability
- Cost factor
- Land impact
- Food-water security
- New fuel has to meet the performance standards of ASTM
- Chemical and physical properties – different

source: Internet
Introduction / Motivation

- Abundance of Natural gas in Qatar instigated interest in “Gas-to-Liquid (GTL)” fuel as drop-in fuel for aviation engines
- Qatar Science and Technology Park
- Academia - Industry Consortium Research
- Properties
- Combustion
- Performance

- Part-1: High altitude relight ignition tests at R-R, UK
- Part-2: Emission tests at R-R, USA
- Part-3: Combustion studies at DLR, Germany
- Part-4: Atomization study at TAMUQ, Qatar
GTL Fuels: Shell

Gas-To-Liquid (GTL): liquid fuel synthesized from Natural gas using Fischer-Tropsch

- Effect of fuel composition on combustion:
  - Carbon range
  - Iso-to-normal paraffin ratio
  - Cyclic content

- Five GTL fuels – Shell
  - Two commercial fuels
    - Bintulu GTL - Malaysia
    - Pearl GTL - Qatar
  - Three blends:
    - (Bintulu + “ShellSol”)

- Reference fuel: Conventional “Jet A-1”

[Bauldreay et al., 2011]
## Fuel properties: Shell

<table>
<thead>
<tr>
<th>Properties @ 20°C</th>
<th>Blend-1</th>
<th>Bintulu (CSPK 1)</th>
<th>Blend-3</th>
<th>Blend-2</th>
<th>Pearl (CSPK 2)</th>
<th>Jet A-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>746</td>
<td>738</td>
<td>751</td>
<td>763</td>
<td>749</td>
<td>790</td>
</tr>
<tr>
<td>Viscosity (mm²/s)</td>
<td>1.36</td>
<td>1.37</td>
<td>1.46</td>
<td>1.60</td>
<td>1.55</td>
<td>1.68</td>
</tr>
<tr>
<td>Surface tension (mN/m)</td>
<td>23.8</td>
<td>23.5</td>
<td>24.1</td>
<td>24.2</td>
<td>23.9</td>
<td>26.8</td>
</tr>
<tr>
<td>H/C ratio (measured)</td>
<td>2.2</td>
<td>2.3</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>1.92</td>
</tr>
<tr>
<td>Iso-paraffins (% Wt)</td>
<td>73.3</td>
<td>55.7</td>
<td>48.4</td>
<td>58.1</td>
<td>64.8</td>
<td>NA</td>
</tr>
<tr>
<td>Normal paraffins (% Wt)</td>
<td>26.0</td>
<td>43.4</td>
<td>36.5</td>
<td>26.7</td>
<td>29.8</td>
<td>NA</td>
</tr>
<tr>
<td>Iso-to-normal paraffin ratio</td>
<td>3.3</td>
<td>1.6</td>
<td>1.5</td>
<td>2.4</td>
<td>2.5</td>
<td>NA</td>
</tr>
<tr>
<td>Naphthenes (% Wt)</td>
<td>0.4</td>
<td>0.5</td>
<td>15.4</td>
<td>15.6</td>
<td>5.4</td>
<td>NA</td>
</tr>
<tr>
<td>Carbon Cut</td>
<td>Narrow</td>
<td>Narrow</td>
<td>Narrow</td>
<td>Wide</td>
<td>Wide</td>
<td>NA</td>
</tr>
<tr>
<td>Narrow (C7-C13) / Wide (C7-C16)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distillation Characteristics (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T50 - T10</td>
<td>8.4</td>
<td>16.6</td>
<td>8.4</td>
<td>10</td>
<td>9.4</td>
<td>28.5</td>
</tr>
<tr>
<td>T90 - T10</td>
<td>20.7</td>
<td>22.5</td>
<td>21.2</td>
<td>27.5</td>
<td>28.7</td>
<td>68.3</td>
</tr>
</tbody>
</table>

- Calorific value (LHV as per D4809 standard): 43.3 ~ 44.2 MJ/kg
Part-1: Relight Ignition

- High altitude relight ignition tests
- Sub-atmospheric combustion rig – Rolls-Royce, Derby-UK
- Limits of ignition boundary tested at two combustion inlet air pressures

(Rolls-Royce-UK facility equipped with DLR diagnostics)

- Proceedings of ASME Turbo Expo 2011: Power for Land, Sea and Air, June 6-10, 2011, Vancouver, Canada:
  - Darren et al., (2011), GT2011-45487
  - Thomas et al., (2011), GT2011-45510

(RR-UK, DLR-Germany, TAMUQ-Qatar)
Part-2: Emission Tests

- Emission characteristics: NO$_x$, CO, CO$_2$, UHC, and smoke number
- IP - Combustion chamber facility at RR-Indianapolis, USA
- Test conditions - represent different stages of aircraft engine cycle – ICAO standards
- Both Main & pilot-scale nozzles were used in emission tests

Emission Tests Outcome:

- At a given combustor operating condition, GTL produced less smoke than Jet A-1
- Under some cases, GTL produced more NOx than Jet A-1 fuel
- Further studies are necessary to gain more insights
Part-3: Combustion studies

- Laminar flame speed measurements at atmospheric conditions

- Ignition delay measurements: Shock tube

- Surrogate chemical kinetics – GTL fuel

- Kick et al., Energy 43 (1), 111-123, 2012
- Slavinskaya et al., “Surrogate Model Design for GTL Kerosene”, 50th AIAA Aerospace Sciences Meeting and Exhibit, Tennessee, USA, 9-12 Jan, AIAA-2012-0977.
Part-4: Sprays Characteristics

Need for spray characteristics?

- Change in physical properties, viscosity, density and surface tension affects the fuel “atomization” characteristics

- Atomization $\rightarrow$ fuel-air mixture $\rightarrow$ Combustion $\rightarrow$ Emissions

“Microscopic” spray characteristics: Droplet size and velocity distribution (GTL vs Jet A-1)

Optical Diagnostic techniques

- Plane-wise (Global) (Global Sizing Velocimetry, GSV) TSI Inc., USA
- Point-wise (Local) (Phase Doppler Anemometry, PDA) Dantec Dynamics, Denmark
Fringe spacing is most “insensitive” to refractive index at 60° (Pan et al. 2005)

Light scattered by the droplets exhibit angular oscillations (fringes)

Droplet size is proportional to the fringe spacing (Pan et al. 2005)

Droplet size measurement limits*

$27 \mu m < d < 2 mm$

* Limits vary with,
  - camera resolution, defocus distance, Magnification, Aperture size

Imaging details

- 200 image pairs (2Hz frame rate)
- 1600x1200/ binning (2x2)
- defocus distance: 135 mm
- Aperture number: 4
PDA Technique

- 2-D PDA system
- $\lambda = 514\text{nm (axial)}$ and $488\text{nm (radial)}$
- Diameter – Doppler burst phase shift
- Velocity – Doppler burst frequency

- Receiver probe is positioned at $42^\circ (\phi)$
- Data sampling: 10,000 samples or 15s
- Results presented are an average of three best trials
- Validation: Diameter (60-80%)
  Velocity (80-90%)

Lorenz-Mie scattering theory

Transmitter and receiver probe arrangement

Lorenz-Mie scattering theory

Measurement volume

Fringes

Transmitter

Nozzle

radial direction ($r$)

axial direction ($x$)

Receiver

514 nm

488 nm

Courtesy: Dantec Dynamics
Experimental Facility

- Three modules – Pump, Spray and Optics
- High pressure fuel supply loop
- Nozzle supplied by RR-UK is mounted on a traversing system
- Injection pressure is measured just upstream of the nozzle
- GSV & PDA systems are integrated to the facility

Pump Module

Spray & Optics Module
Experiment Details

- Inert (N$_2$) ambiance at atmospheric condition (101325 Pa and 298K)

- Pilot-scale pressure-swirl nozzle:
  Fuel injection pressures are 0.3, 0.6, and 0.9 MPa (SD ±3%)

- Injection pressures are chosen based on RR-UK suggestions

- Spray is symmetric and measurements are carried out only on one side of the spray

- The field of view for GSV is decided based on the facility dimensions, camera lens capability. Radial direction is covered in two steps
The difference in size distribution beyond 300 µm is insignificant among the fuels and not shown.

However, full diameter range is used to calculate Sauter Mean Diameter (SMD).

Increase in injection pressure slightly increases the number of smaller droplets as expected.

Distribution trends are similar.

[Kumaran & Sadr, ICLASS, 2012]
[Kumaran & Sadr, Atomization and Sprays, 24 (7), 575-597, 2014]
- Size distributions trends at NS2 are similar to that in NS1
- The probability is slightly higher at NS2 than NS1
- Mean droplet diameters ($d_{10}$ and $d_{32}$) decrease with an increase in injection pressure as expected
- The mean diameter trends are consistent with those of the size distributions

[Kumaran & Sadr, ICLASS, 2012]
[Kumaran & Sadr, Atomization and Sprays, 24 (7), 575-597, 2014]
### Operating Parameters

#### Transmitting optics
- **Focal length**: 400 mm
- **Beam spacing**: 38 mm
- **Beam waist**: 1.35 mm

#### Receiving optics
- **Focal length**: 500 mm
- **Scattering angle**: 42°
- **Aperture mask**: Mask-B

#### Measurement volume
- **Diameter (dx)**: 189 µm
- **Length (dz)**: 3.97 mm
- **Fringe spacing**: 5.27 µm
- **No. of Fringes**: 36

### User Settings

- **Photomultiplier Voltage (PMV)**: 1200 V
- **Signal Gain (SG)**: 24 dB
- **Signal-to-Noise ratio (SNR)**: -2.0 dB
- Data rate at last measurement location is less than 3% of the maximum value at that axial location.

- Lower values of viscosity and surface tension for CSPK 1: faster disintegration and dispersion of droplets when compared to that in Jet A-1 fuel.

Only CSPK 1 & Jet A-1 are shown as they show maximum difference in their fuel properties.
Sauter Mean Diameter ($d_{32}$)

$\frac{d_{32}}{d_2} = \frac{d_3}{d_2}$

- SMD increases with increase in radial distance for all the fuels as expected in a pressure-swirl nozzle.

- CSPK 2 and Jet A-1 trends are similar as their fuel properties are narrowly separated.

[Controlled conditions: 0.3MPa, 0.9MPa]


Micro Scale Thermo-Fluids Lab
Spatial distribution of droplets detected using GSV

“PDA measurements” at three radial locations for Jet A-1 at 0.3 MPa

- CSPK 1 0.9MPa
- CSPK 1 0.3MPa
- Jet A-1 0.3MPa

Spatial distribution

- NS0
- NS1
- NS2

Radial direction, mm

Probability, %

Diameter, µm

(#/cm³: ~ 25,000)

(#/cm³: ~ 14,000)

(#/cm³: ~ 7,000)
Takeaways

GTL vs Jet A-1

✓ Better ignition limits at high altitude conditions
✓ Better smoke performance

More NO\textsubscript{x} emissions than Jet A-1

✓ Laminar flame speeds are slightly higher
✓ Overall spray characteristics are similar at atmospheric conditions

- Essential to study spray characteristics at actual combustor conditions
Future directions

Spray Characteristics

@ elevated ambient conditions
- TAMUQ / NEU / GE-QSTP (NPRP-7-1499-2-523)

Role of fuel additives
- Currently in progress

Other alternative fuels

Mixing / Combustion aspects

Only a drop in the ocean...

every drop counts! 😊
Acknowledgement

- Rolls Royce, UK
  - Mr. John Moran, Combustion Specialist

- DLR, Germany team
  - Dr. Patrick LeClercq
  - Dr. Thomas Mosbach

- Shell (UK & Qatar) team
  - Dr. Joanna Bauldreay, (UK)
  - Mr. Ali M. Al-Sharshani, (QSRTC)

- late Prof. Chris Wilson, University of Sheffield
- Dr. Mahesh Panchagnula, Indian Institute of Technology Madras (IITM)

Thank You!
References


Mean Droplet Diameter ($d_{10}$)

Compared across fuels at,

- $X=40$ mm
- $X=80$ mm
- 0.3 MPa
- 0.9 MPa
Sauter Mean Diameter ($d_{32}$)

Compared across fuels at,

- $X=40\text{ mm}$
- $X=80\text{ mm}$

![Graphs showing Sauter Mean Diameter ($d_{32}$) comparison across fuels at different X positions and pressures.](image-url)
Verification

- Mono-disperse droplet generator (MDG) produces droplet diameters of known size.
- Water is used to generate droplet diameters of known size.
- GSV, PDA and expected diameters are within 10% agreement.

![MDG-100 Setup (TSI Inc.,)](image)

![Syringe pump, Reservoir head, Signal generator](image)

![Water droplet stream from MDG](image)
Fuel preparatory steps are the same for GSV & PDA measurements.
SMD Comparison

- Estimated SMD using Lefebrve’s (1987) empirical relation for Simplex nozzle,

\[ SMD = 2.25 \cdot \sigma^{0.25} \cdot \mu^{0.25} \cdot \dot{m}_t^{0.25} \cdot \Delta P_t^{-0.5} \cdot \rho_a^{-0.25} \]

**GSV**
- The SMD determined using GSV data is found to be higher than the estimated value by a maximum of 26% and 48% for 0.3MPa and 0.9MPa, respectively.

<table>
<thead>
<tr>
<th>Injection pressure</th>
<th>SMD, µm (Estimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSPK 1</td>
</tr>
<tr>
<td>0.3MPa</td>
<td>129</td>
</tr>
<tr>
<td>0.9MPa</td>
<td>93</td>
</tr>
</tbody>
</table>

**PDA**
- Droplet diameters that are collected within a common time window across all radial locations at a given axial location are used for global SMD calculation.
- Global SMD is found to be lower than the estimated SMD by a maximum of 28% and 16% for 0.3MPa and 0.9MPa, respectively.

<table>
<thead>
<tr>
<th>Injection pressure</th>
<th>SMD, µm (GSV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSPK 1</td>
</tr>
<tr>
<td>0.3MPa</td>
<td>155</td>
</tr>
<tr>
<td>0.9MPa</td>
<td>136</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injection pressure</th>
<th>SMD, µm (PDA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSPK 1</td>
</tr>
<tr>
<td>0.3MPa</td>
<td>96</td>
</tr>
<tr>
<td>0.9MPa</td>
<td>81</td>
</tr>
</tbody>
</table>

[Kumaran & Sadr, ASME Turbo Expo 2013, GT2013-95761]
Overall shape and trends are similar between the fuels.

Typical standard deviation is shown as error bars only at two axial locations to facilitate the comparison.

[Kumaran & Sadr, ASME Turbo Expo 2014, GT2014-25842]
Fuel with lower viscosity and density (CSPK 1) exhibits higher droplet mean axial velocity.

Trends are inline with those observed for the data rate.