Alternative Fuels for Gas Turbine and Jet Engines

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Alternative Fuels for Gas Turbine and Jet Engines: Overall Context

MOTIVATION

**ENERGY**
- Finite resources & Rising fuel cost
- Dependence & Security of supply

Need for Alternative Fuels

**ENVIRONMENT** (*Global Warming*)
- Aviation accounts for 1.6% of global greenhouse gas emissions and is forecasted to contribute to 2.5% of CO2 emissions in 2050
CO2 Emissions from Commercial Airlines Global Fuel Burn (Economic Model)

- Frozen technology 5% p.a. (air traffic growth)
- Fleet replacement by new technology aircraft -1.3% p.a.
- Better aircraft utilisation -0.3% p.a.
- Operational measures -0.1% p.a.
- Infrastructure measures -0.2% p.a.
- Technology retrofits -0.1% p.a.
- Biofuels -0.7% p.a.
- Economic measures -2.2% p.a.

This model comprises the benefits of all measures considered.
Only under very beneficial conditions all of them will be realised.

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CO2 Emissions from Commercial Airlines Global Fuel Burn (Economic Model)
ALTERNATIVE FUELS

- For CO2 reduction in Aviation - Biofuel (3rd generation - algae)
- For security of the Power Industry - Synthetic Fuels (methanol)
Aero Propulsion: Bio Fuels

Technical Issues to be resolved

- Lubrication capabilities
- Systems aggressive?
- Spray formation
- Emissions
- Operability (Extinction, Altitude relight)
- Freezing Point, Flash point

02/2008: Virgin Atlantic successfully flew from London's Heathrow airport to Amsterdam using a biofuel made of a mix of coconut and babassu oil.
Biofuels Characteristics

- Made from plants or animal fat.
- Organic compounds (C,H,O).
- Biodegradable
- Sources: Corn, soybeans, algae, jatropha, palm oil, coconut, babassu, vegetable oil and more.
- Zero/low aromatic content
- Zero/low sulfur content
- reduced emission of pollutants:
  - Typically Lower, CO, PAH & soot.
  - Lower Toxic, mutagenic and carcinogenic materials
Biofuel classification

- Alcohol: short chained molecule (high O/C ratio), Oxygenated (R-OH), low calorific value (IC Engines)
- Biodiesel: Fatty Acid Methyl Ester (long carbon chain), Oxygenated, higher O/C ratio, intermediate calorific value (Diesel Engines).
- Bio SPK - Synthetic Paraffinic kerosene, 100% Paraffin, no aromatic, higher calorific value (Jet engines)
### Fuel composition

<table>
<thead>
<tr>
<th>Molecule type</th>
<th>Kerosene (%)</th>
<th>Diesel (%)</th>
<th>Biojet (HRJ) (%)</th>
<th>Biodiesel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal and iso- Paraffin</td>
<td>50-65%</td>
<td>25-50%</td>
<td>95.1%</td>
<td>0%</td>
</tr>
<tr>
<td>Cyclo-Paraffin</td>
<td>20-30%</td>
<td>20-40%</td>
<td>4.9%</td>
<td>0%</td>
</tr>
<tr>
<td>Aromatics and Poly-aromatics</td>
<td>10-20%</td>
<td>15-40%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Olefin</td>
<td>5%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Fatty Acid Methyl Ester (FAME)</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
</tr>
</tbody>
</table>
# Kerosene and Biojet comparison

<table>
<thead>
<tr>
<th></th>
<th>Kerosene</th>
<th>Biojet*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Formula</strong></td>
<td>C12H23</td>
<td>C11.93H25.76</td>
</tr>
<tr>
<td><strong>Molecular weight</strong></td>
<td>167</td>
<td>168.92</td>
</tr>
<tr>
<td><strong>H/C ratio</strong></td>
<td>1.92</td>
<td>2.16</td>
</tr>
<tr>
<td><strong>Hydrogen content (%mass)</strong></td>
<td>13.77</td>
<td>15.25</td>
</tr>
<tr>
<td><strong>Density at 15°C (kg/m³)</strong></td>
<td>775-840</td>
<td>765.4</td>
</tr>
<tr>
<td><strong>Viscosity at-20°C (mm²/s)</strong></td>
<td>Max. 8</td>
<td>5.11</td>
</tr>
<tr>
<td><strong>Surface tension at 20°C (mN/m)</strong></td>
<td>23-32</td>
<td>24.4</td>
</tr>
<tr>
<td><strong>Aromatic content (v%)</strong></td>
<td>Max. 25</td>
<td>0</td>
</tr>
<tr>
<td><strong>Lower heating value (MJ/kg)</strong></td>
<td>Min 42.8</td>
<td>43.8</td>
</tr>
<tr>
<td><strong>Flash point (°C)</strong></td>
<td>Min. 38</td>
<td>49</td>
</tr>
<tr>
<td><strong>Freezing point (°C)</strong></td>
<td>Max. -47 (Jet A-1, JP8)</td>
<td>-41.1</td>
</tr>
<tr>
<td><strong>Auto-ignition temperature (°C)</strong></td>
<td>245</td>
<td>222</td>
</tr>
</tbody>
</table>

* Hydro-treated Renewable Jet (HRJ) - DynamicFuels LLC. (2014)
The combustor model

Fuels tested:
- kerosene
- Diesel
- methanol
- biojet
- biodiesel

Swirl
Fuel injector
Temperature profile

<table>
<thead>
<tr>
<th></th>
<th>Measured Exhaust temperature K</th>
<th>Measured Difference</th>
<th>Adiabatic Flame Temperature K</th>
<th>Simulated Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene 0.646</td>
<td>1025</td>
<td>Δ=16K</td>
<td>1734</td>
<td>Δ=17K</td>
</tr>
<tr>
<td>Bio-SPK 0.642</td>
<td>1009</td>
<td></td>
<td>1717</td>
<td></td>
</tr>
<tr>
<td>Kerosene 0.539</td>
<td>999</td>
<td>Δ=11K</td>
<td>1519</td>
<td></td>
</tr>
<tr>
<td>Bio-SPK 0.539</td>
<td>988</td>
<td></td>
<td>1508</td>
<td>Δ=11K</td>
</tr>
</tbody>
</table>
**Emissions**

*normalized to 15% O₂*

\[
X_{i, ppm@15%O₂} = X_{i, ppm} \cdot \left( \frac{21 - 15}{21 - X_{i,O₂, rael}} \right)
\]

- Kerosene 0.646
- Kerosene 0.539
- Bio-SPK 0.642
- Bio-SPK 0.539

Biojet generated higher NOx and lower CO and UHC
METHANOL - AN ALTERNATIVE FUEL FOR TRANSPORTATION AND INDUSTRY

Considered as synthetic fuel & an immediate alternative fuel

Pros:  Availability (made of natural gas)
        Low cost,
        Can be transported & stored
        Good combustion properties

Cons:
        Low energy density
        Can emit formaldehyde and Acrolein (toxic)
        Corrosive
        Low volatility
METHANOL COMBUSTION

Methanol has lower carbon content & lower combustion temperature and therefore has lower luminescence & lower radiation (than heavy oil)

(ref: Dor Chemicals Ltd.)
Effect of fuel type on atomization

Methanol require twice as much fuel (\& bigger fuel nozzle) as compared to kerosene for the same heat release.

a) nozzle 1.25G/h (kerosene)

b) nozzle 2.75G/h (methanol)

Radial SMD distributions at the different inlet liquid pressures, 50mm from the nozzle.
Evaporation time ratio Vs. gas - liquid temperature difference for Kerosene and methanol corresponding to equal thermal power
Evaporation rate [kg/s] of kerosene and methanol for equal thermal power;
(a) – complete evaporation point for kerosene;
(b) - complete evaporation point for methanol.

Evaporation of kerosene and methanol fuel sprays in heated air stream 600K & 800K (for equal thermal power)
IGNITION DELAY - CHEMKIN SIMULATION
(Φ=0.5, Tin = 1000K, P=1bar)

Evolution of heat release for kerosene and methanol combustion

Variation of ignition delay with inlet temperature, kerosene – methanol

At low temperatures, methanol - air mixtures burn slower

Ignition delay
CFD SIMULATIONS – swirl stabilized burner

- Narrow gap for cooling
- Fuel injector
- Core flow region
The three different flow path lines through the combustor:

- Core flow at the center of the burner
- Flow through the swirl vanes
- Flow the outer gap
Droplet diameter evolution

**reactive condition**

Kerosene and methanol fuel sprays for equal thermal power

Evaporation process is slower for methanol
CFD results - Contours of total temperature

**Kerosene**
(Texit = 1493K)

**methanol**
(Texit = 1439K)

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**Incomplete Methanol Combustion**
(REQUIRES LONGER DISTANCE FOR COMPLETION)

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**Equal thermal power, EDM, single global reaction.**

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**KEROSENE AND METHANOL COMBUSTION FOR EQUAL THERMAL POWER**
Combustion model: EDC (Li Mechanism - 18 species and 84 reactions)

(\text{CH}_2\text{O} \text{ max} = 3178 \text{ ppm}, \text{CH}_2\text{O} \text{ exit} = 0.014 \text{ ppm})
• Methanol has larger fuel flow rate, longer evaporation & longer ignition delay.

• Methanol flame is delayed and requires longer distances for its completion.
Due to lower combustion temperature, methanol combustion generates less NOx.
CO concentrations (@15%O\textsubscript{2}, non insulated combustor)

Due to overall slower combustion process, methanol requires larger distance to complete combustion.
Results and conclusions (biojet Vs. kerosene):

- 100% paraffin, shorter C chain, higher H/C and consequently less CO and UHC
- Biojet has higher adiabatic temperature and consequently higher NOx
- Still very high cost
Results and Conclusions
(biojet & methanol Vs. kerosene):

- Biojet is made of 100% paraffin, shorter C chain, higher H/C and consequently lower CO and UHC emissions.
- Biojet has higher adiabatic flame temperature and consequently emit higher Nox.
- Biojet has much high cost
- Methanol is an oxygenated molecule (CH3OH).
- For equal thermal power, methanol liquid flow rate is higher, evaporation takes longer time and it has shorter ignition delay. As a result requires longer distances for its completion.
- Methanol has competitive cost
- More works should be performed to assure compatibility with regards to emissions (formaldehydes & acrolein) and operational limitations (LBO, radiative properties and more).
- Methanol is relevant for gas turbines (power stations) and as an emergency fuel for aviation, certain adaptation is requires in fuel storage & supply system. In some applications, dimensions have to be increased, else combustion will terminate as incomplete.
THANK YOU
the Turbo and Jet Engine Laboratory
Climate assessment

Climate is perturbed much differently by individual species.

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>NOₓ</th>
<th>Contrails</th>
<th>water vapour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependence on location</td>
<td>no</td>
<td>very</td>
<td>very</td>
<td>very</td>
</tr>
<tr>
<td>Perturbation lifetime</td>
<td>Decades</td>
<td>O₃ weeks</td>
<td>hours</td>
<td>Troposphere</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(CH₄ months)</td>
<td></td>
<td>(0~10Km) -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>hours</td>
</tr>
<tr>
<td>Climate impact</td>
<td>Decades</td>
<td>Decades</td>
<td>Decades</td>
<td>Decades</td>
</tr>
</tbody>
</table>

Ref: Volker Grewe
DLR-Oberpfaffenhofen, Germany
TEMPERATURE DISTRIBUTION ALONG THE COMBUSTOR TUBE  
(insulated combustor)

**CFD SIMULATIONS**

**EXPERIMENTAL RESULTS**

- **Kerosene**
  - $\Phi=0.5$
  - $\Phi=0.67$
  - $\Phi=0.49$
  - $\Phi=0.47$

- **Methanol**
  - $\Phi=0.5$
  - $\Phi=0.72$
  - $\Phi=0.49$
  - $\Phi=0.38$
## Kerosene and methanol comparison, summarized results

Equivalence ratio ER=0.61

<table>
<thead>
<tr>
<th>Combustion Model</th>
<th>Wall Temp., K</th>
<th>T max, K</th>
<th>T, K (average exit)</th>
<th>NOx, ppm(exit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD. Kerosene. Non-adiabatic</td>
<td>850</td>
<td>2404</td>
<td>1452</td>
<td>45.7</td>
</tr>
<tr>
<td>Experimental. Kerosene. Non-adiabatic</td>
<td>870</td>
<td>-</td>
<td>1430 (CORRECTED)</td>
<td>55</td>
</tr>
<tr>
<td>CFD. Methanol. Non-adiabatic</td>
<td>880</td>
<td>2340</td>
<td>1352</td>
<td>10.6</td>
</tr>
<tr>
<td>Experimental. Methanol. Non-adiabatic</td>
<td>823</td>
<td>-</td>
<td>1380 (CORRECTED)</td>
<td>9.5</td>
</tr>
</tbody>
</table>
“Cold” simulation results

Recirculation zone moves

Velocity vectors colored by velocity magnitude, m/s

The 54th Israel Annual Conference on Aerospace Sciences
Actual temperature estimation from thermocouple reading

Heat (energy) balance

\[ hA(T_g - T_{tc}) \approx \varepsilon\sigma A(T_{tc}^4 - T_{wall}^4) \]  \hspace{1cm} (1)

Here

\[ h = Nu\lambda / d \]

\[ Nu = 2 + (0.4Re_{dtc}^{0.5} + 0.6Re_{dtc}^{2/3})Pr_g^{0.4}(Pr_g/Pr_{wall})^{0.25} \]

* (For sphere in laminar flow)

Solution of equation (1) gives

\[ T_g - T_{tc} \approx 199K \]

Performance Advancements

Evolution in Engines

Kg fuel/h
Kg F

45% REDUCTION

Certification Date

THE 13TH (Bar Mitva) ISRAELI SYMPOSIUM ON JET ENGINES AND GAS TURBINES
Thursday, November 6 2014
New Aircraft Concepts (noise, drag, payload, speed)

BLB configuration and Contra Rotating Open Rotor

NACRE, Airbus (& partners incl. TsAGI)
New Aircraft Concepts, 2005-2008

HISAC, Dassault ( & partners incl. Sukhoi)
Environmentally Friendly High-Speed Aircraft
2005-2009

Low Sonic Boom Family
If we don't do any thing then....

GLOBAL WARMING...
Flight Path 2050 Vision, (propulsion perspective)

- 75% reduction in CO2 emissions per passenger kilometre (cf. ATAG target).
- 90% reduction in NOx emissions.
- 65% reduction of the perceived noise (Reference: 2000).
- Aircraft movements are emission-free when taxiing.

2050
Propulsion: Alternative Fuels

Fuels Interchangeable with Kerosene
- Synthetic Fuels XTL (GTL, BTL, CTL)
  (Gas-to-liquids, Biomass-to-liquids, Coal-to-liquids)
- Kerosene blended with Bio-fuels

BTL Environmental Issues
- Overall C02 balance (production - consumption cycle > 0)
- Bio-Fuels: but no competition with land for food production
- 3rd generation: from algae, biomass

Economic and Regulatory Issues
- Industrial production
- Worldwide availability
- Business case
  Certification
  ETS (Emissions Trading Scheme)


KLM Boeing 777-200 at the gate at JFK Int. Airport, NY.
First flight from Amsterdam. Biofuel made from processed frying fat. March 8 2013, (Courtesy: Boeing)