Alternative Fuels for Gas Turbine and Jet Engines

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Alternative Fuels for Gas Turbine and Jet Engines: Overall Context

MOTIVATION

ENERGY

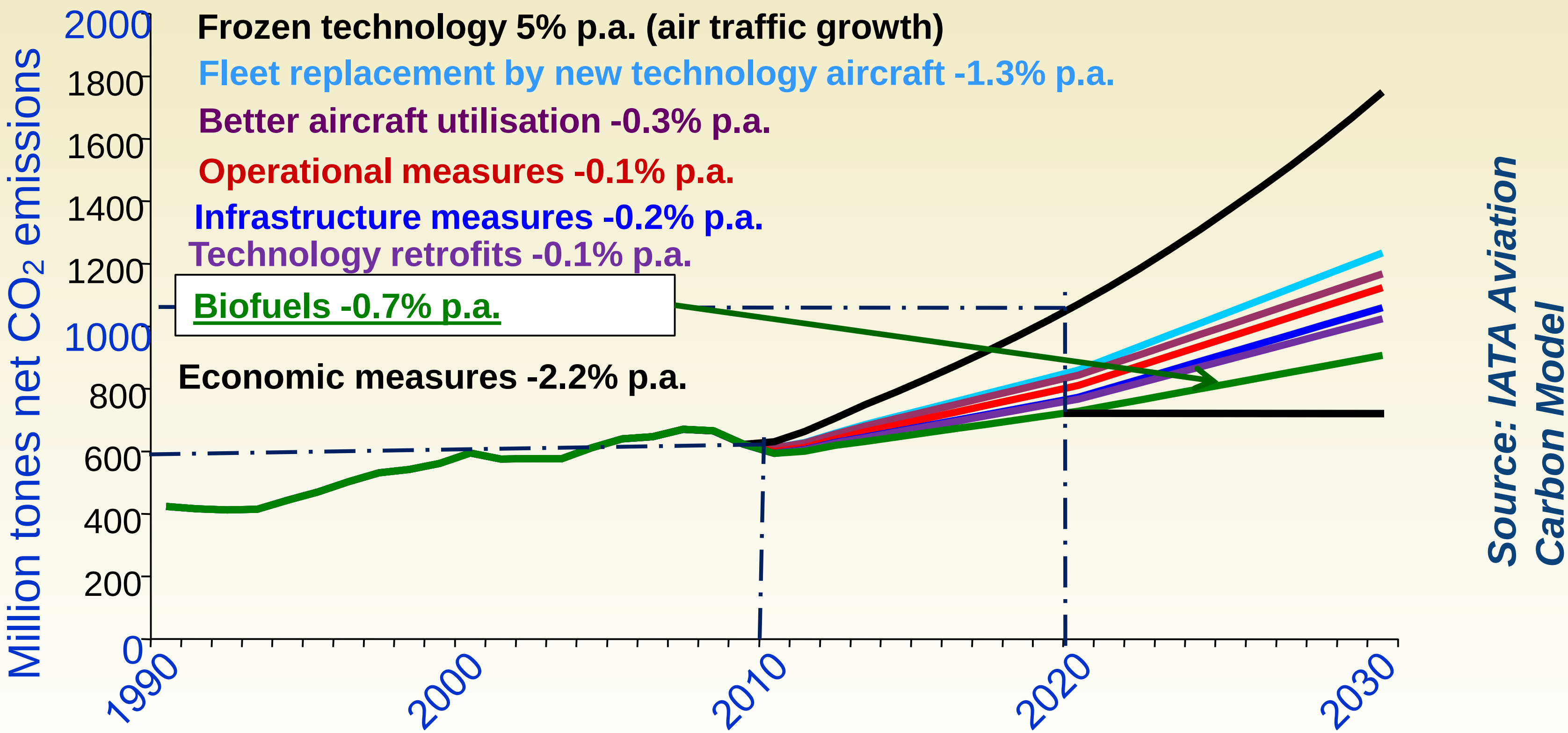
- *Finite resources & Rising fuel cost*
- *Dependence & Security of supply*

→ *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)



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

ALTERNATIVE FUELS

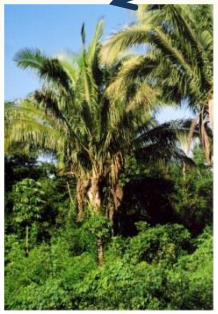
- For CO_2 reduction in Aviation - Biofuel (3rd generation - algae)
- For security of the Power Industry - Synthetic Fuels (methanol)

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.***



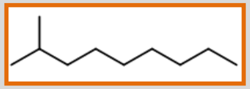
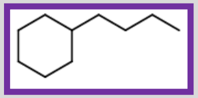
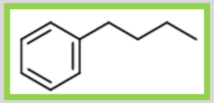
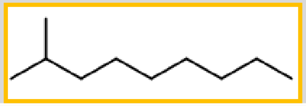
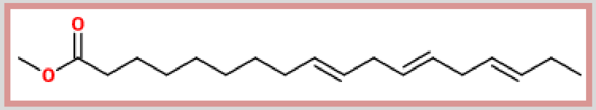
Biofuels Characteristics

- 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

Molecule type	Kerosene	Diesel	Biojet (HRJ)	Biodiesel
Normal and iso- Paraffin 	50-65%	25-50%	95.1%	**0%**
Cyclo-Paraffin 	20-30%	20-40%	4.9%	**0%**
Aromatics and Poly-aromatics 	10-20%	15-40%	**0%**	**0%**
Olefin 	5%	**0%**	**0%**	**0%**
Fatty Acid Methyl Ester (FAME) 	**0%**	**0%**	**0%**	100%

Kerosene and Biojet comparison

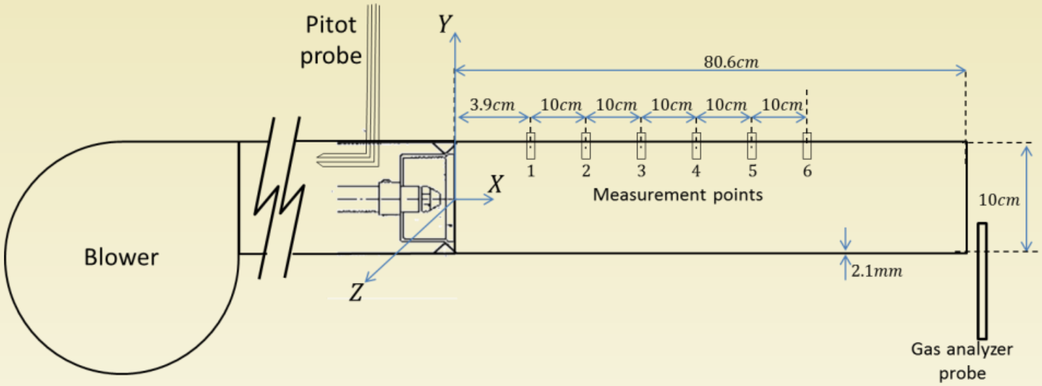
	Kerosene	Biojet*
Formula	C12H23	C11.93H25.76
Molecular weight	167	168.92
H/C ratio	**1.92**	**2.16**
Hydrogen content (%mass)	13.77	15.25
Density at 15°C (kg/m³)	**775-840**	**765.4**
Viscosity at-20°C (mm²/s)	Max. 8	5.11
Surface tension at 20°C (mN/m)	23-32	24.4
Aromatic content (v%)	**Max. 25**	**0**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

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

The combustor model

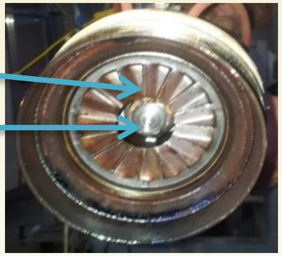
Fuels tested:

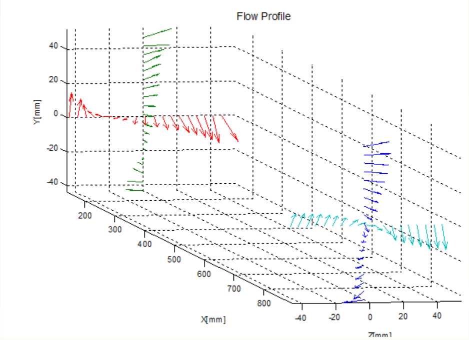
- **kerosene**
- Diese
- methanol
- **biojet**
- biodiesel



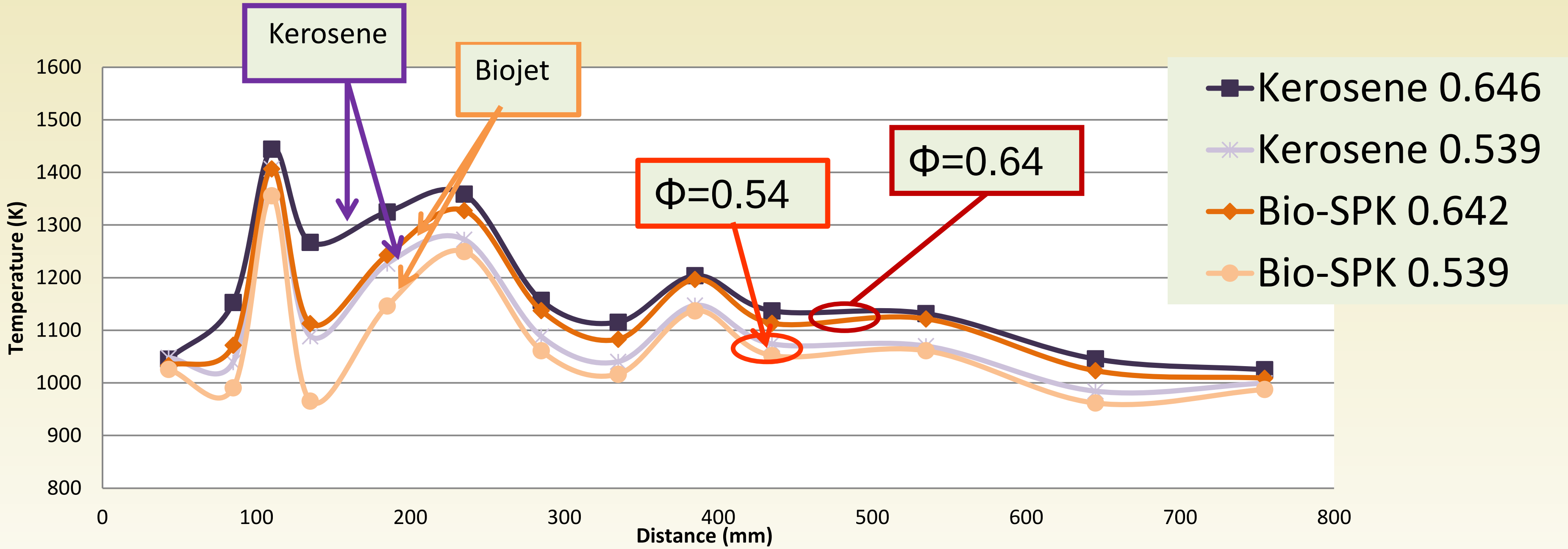
Swirl

Fuel injector



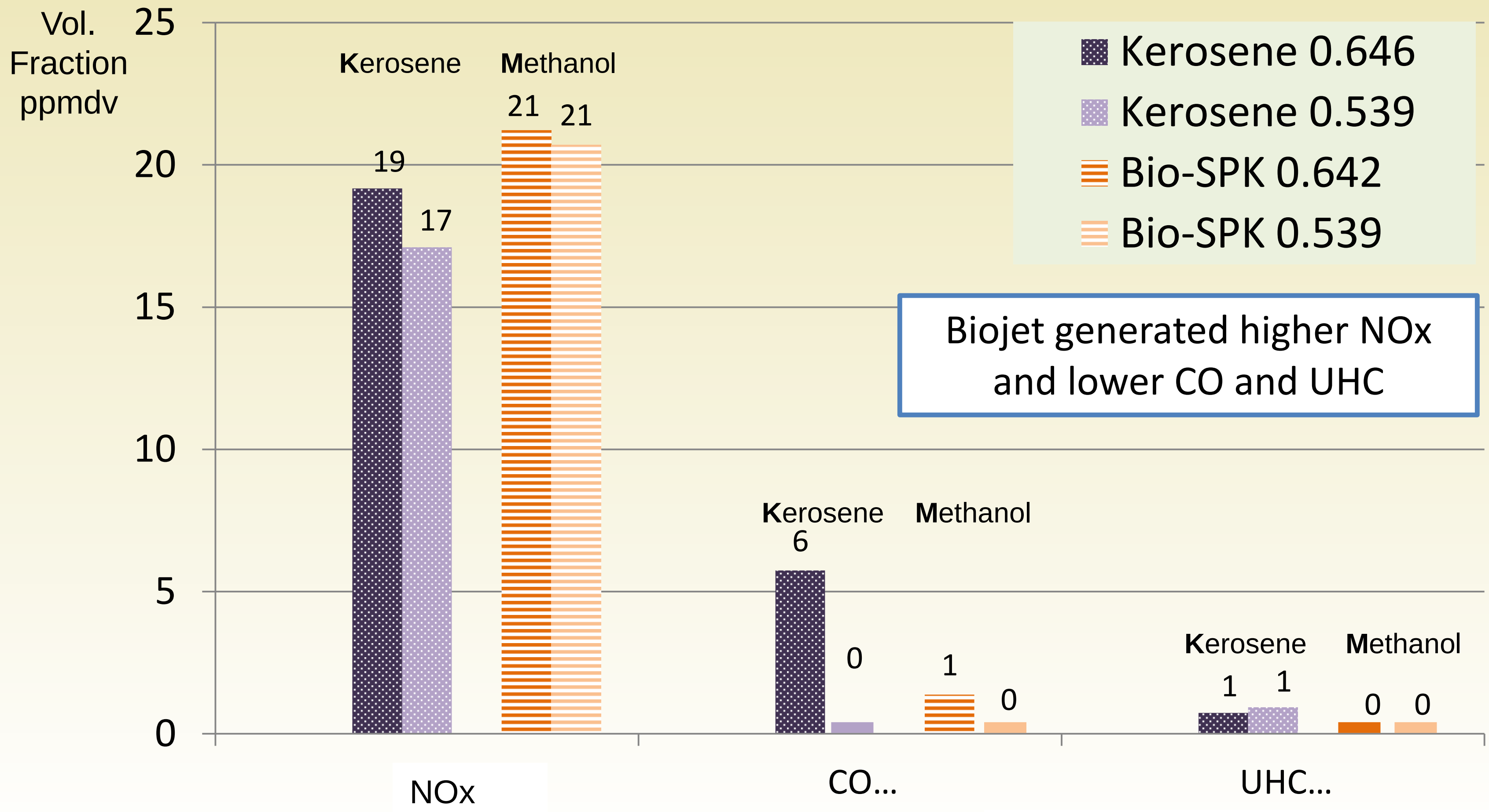


Temperature profile



	Measured Exhaust temperature K	Measured Difference	Adiabatic Flame Temperature K	Simulated Difference
Kerosene 0.646	**1025**	**Δ=16K**	**1734**	**Δ=17K**
Bio-SPK 0.642	1009		1717	
Kerosene 0.539	**999**	**Δ=11K**	**1519**	**Δ=11K**
Bio-SPK 0.539	988		1508	

Emissions*



Biojet generated higher NOx and lower CO and UHC

*normalized to 15%O2

$$X_{i,\,ppm@15\%O_2} = X_{i,\,ppm} \cdot \left(\frac{21-15}{21- X_{\%O_2,\mathrm{rael}}} \right)$$

METHANOL - AN ALTERNATIVE FUEL FOR TRANSPORTATION AND INDUSTRY

Considered as synthetic fuel & an immediate alternative fuel

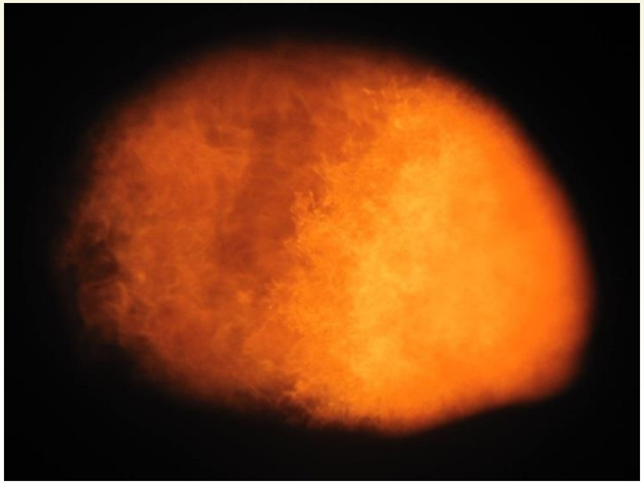
Pros: Availability (made of natural gas)
Low cost,
Can be transported & stored
Good combustion properties

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

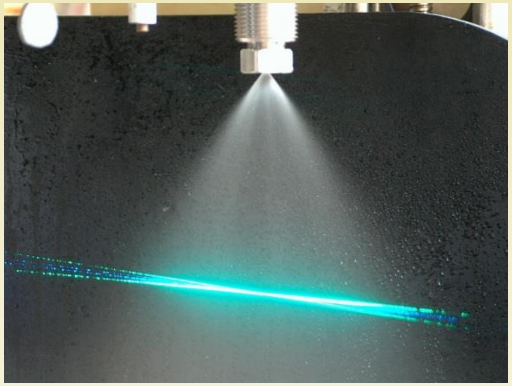
(ref:
Dor Chemicals LTd.)

METHANOL COMBUSTION

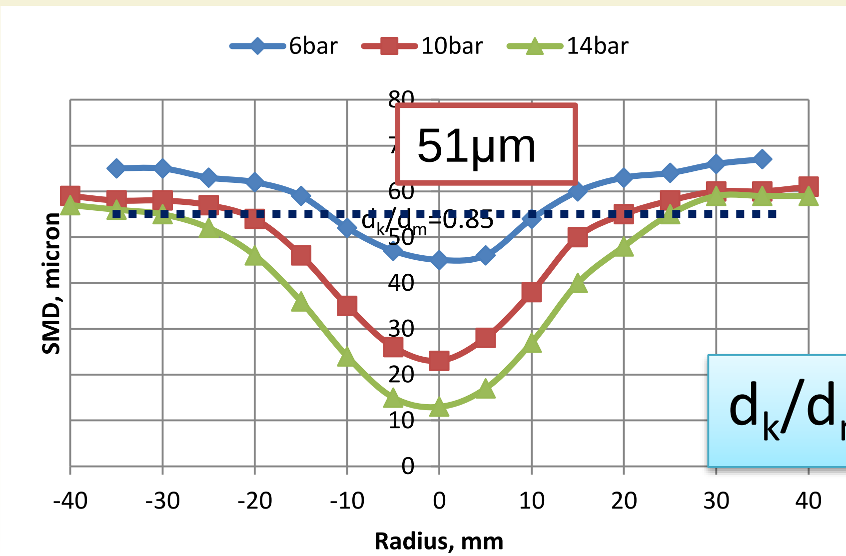
Methanol has lower carbon content & lower combustion temperature and therefore has lower luminescence & lower radiation (than heavy oil)

METHANOL	HEAVY OIL
	

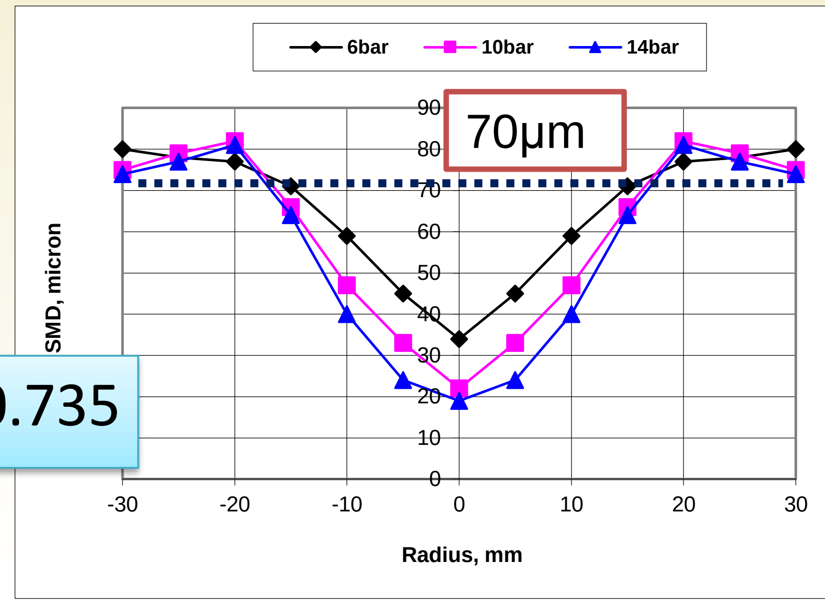
Effect of fuel type on atomization



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



d_k/d_m=0.735



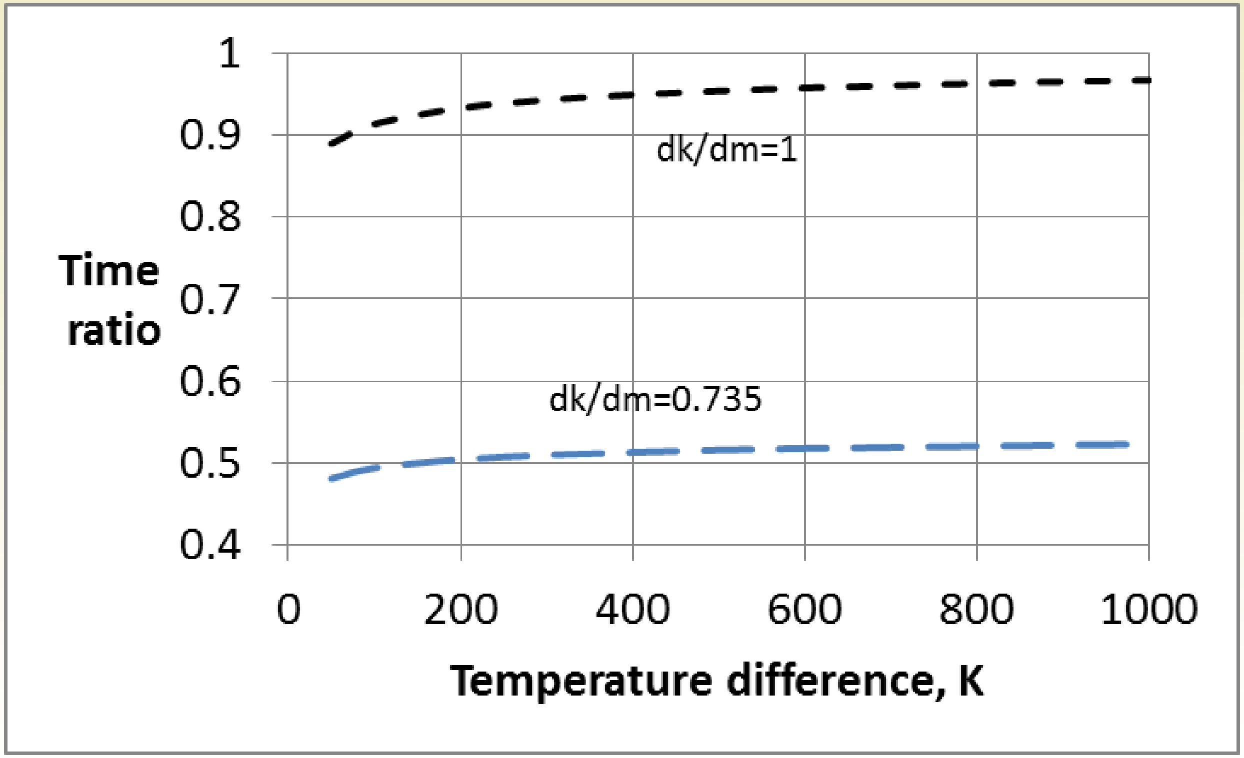
a) nozzle 1.25G/h (kerosene)

b) nozzle 2.75G/h (methanol)

Radial SMD distributions at the different inlet liquid pressures, 50mm from the nozzle.

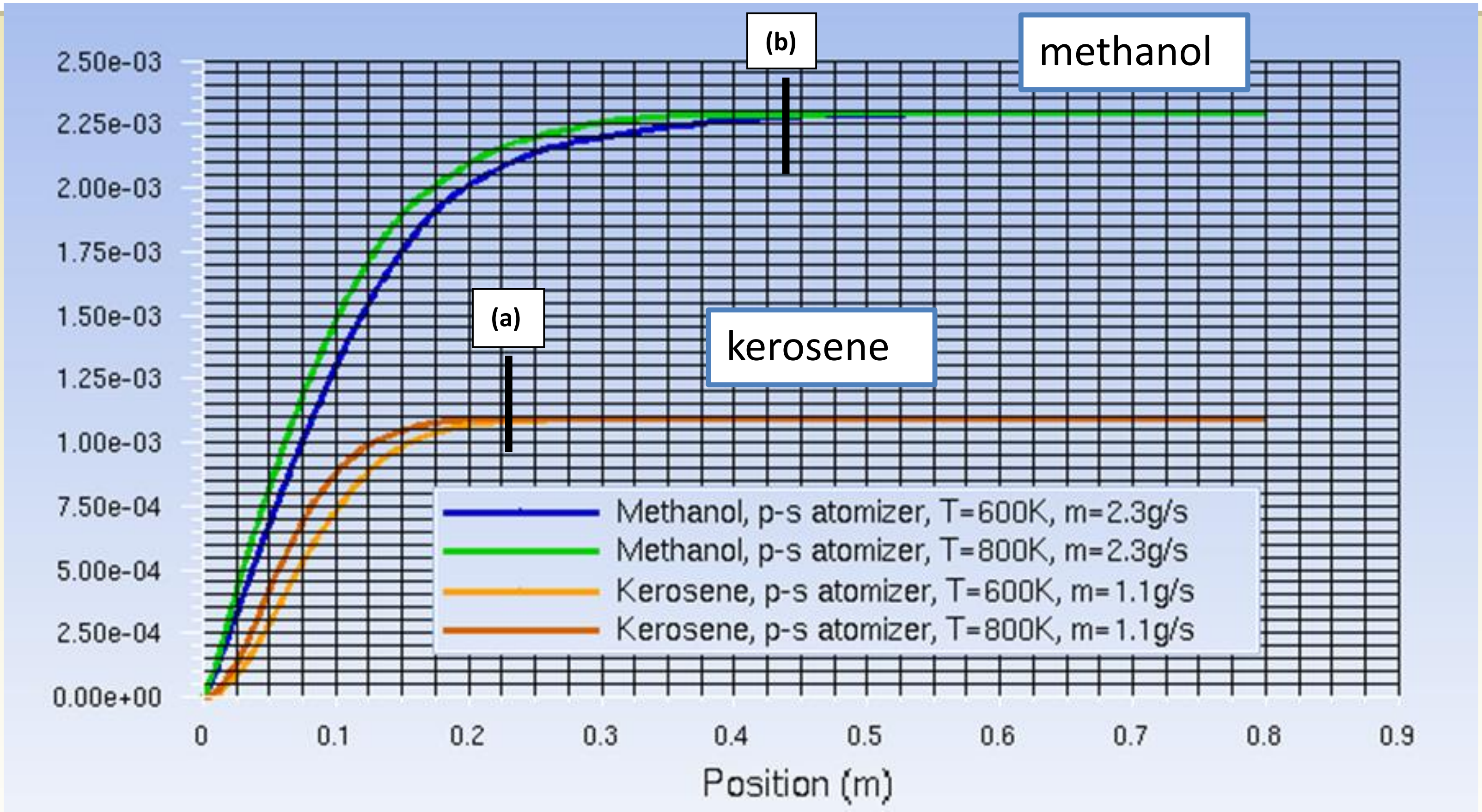
EVAPORATION TIME

$$\tau_{lt} = \frac{d_0^2}{\{8\alpha\left(\rho_g/\rho_l\right)\ln\left[1+\frac{c_p(T_\infty - T_0)}{L_A}\right]\}}$$



Evaporation time ratio Vs. gas - liquid temperature difference
for Kerosene and methanol corresponding to equal thermal power

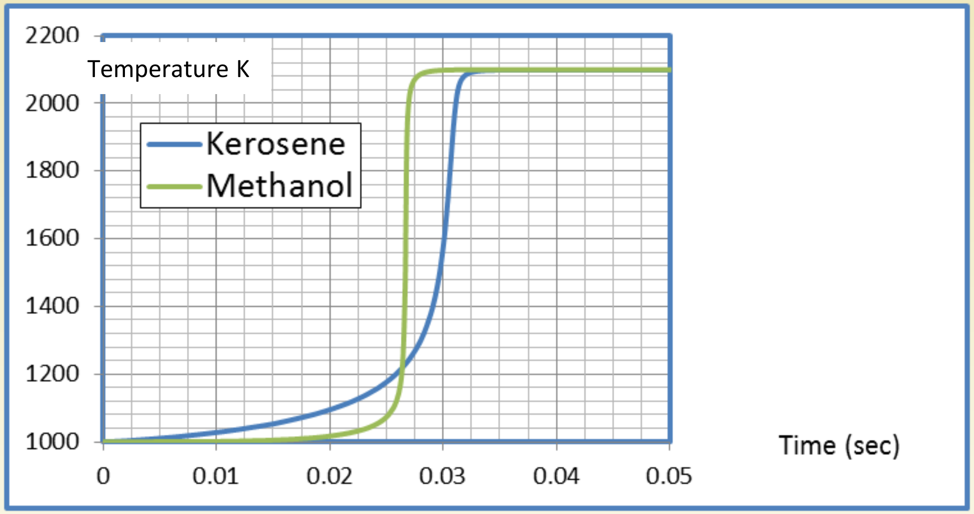
Evaporation rate [kg/s]



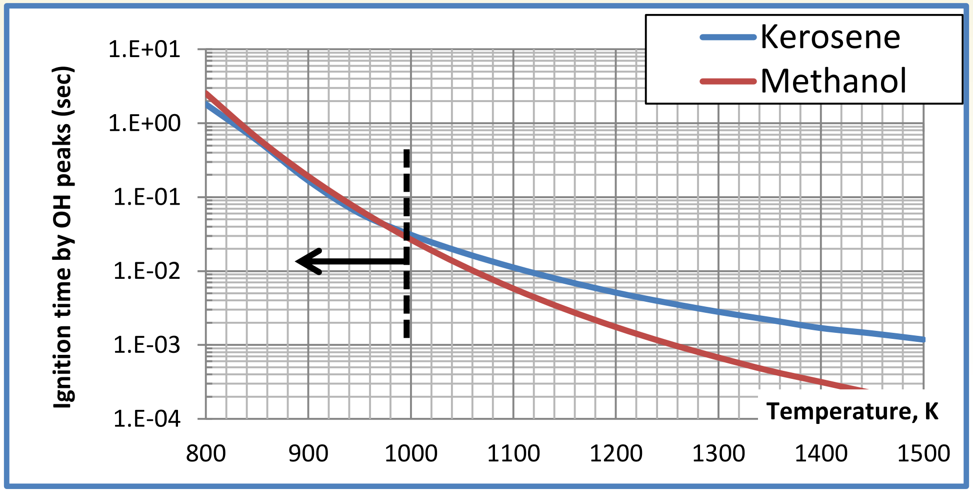
Evaporation rate [kg/s] of kerosene and methanol for **equal thermal power**;
(a) – complete evaporation point for kerosene;
(b) - complete evaporation point for methanol.

IGNITION DELAY - CHEMKIN SIMULATION

(Φ=0.5, Tin = 1000K, P=1bar)



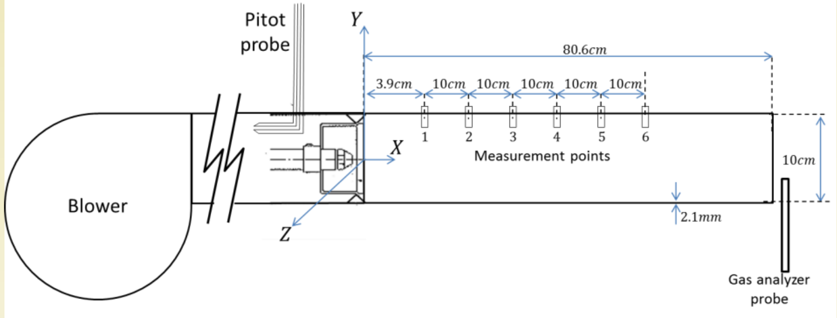
Evolution of heat release for kerosene and methanol combustion

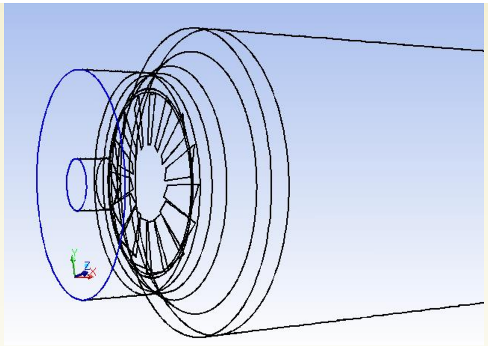


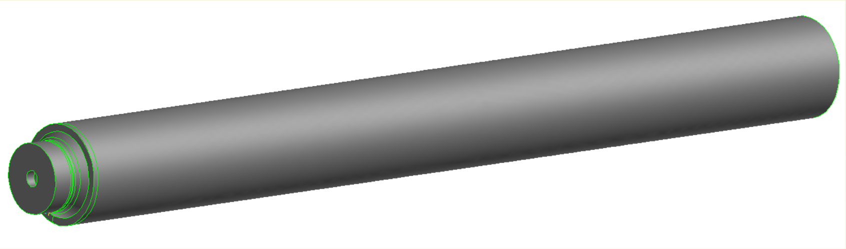
Variation of ignition delay with inlet temperature,
kerosene – methanol

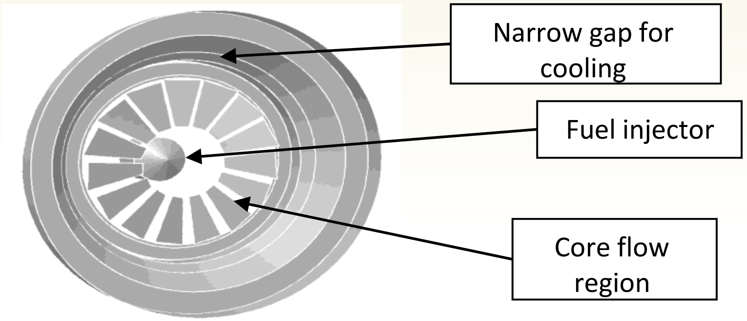
At low temperatures, methanol - air mixtures burn slower

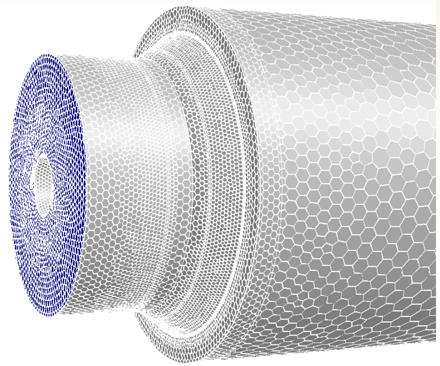
CFD SIMULATIONS – swirl stabilized burner



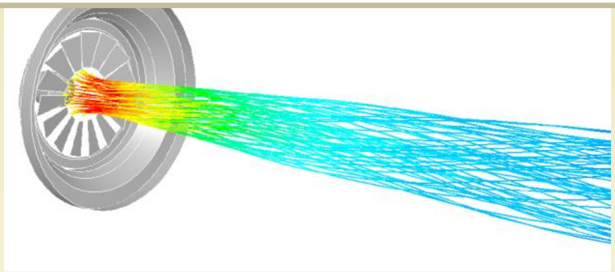




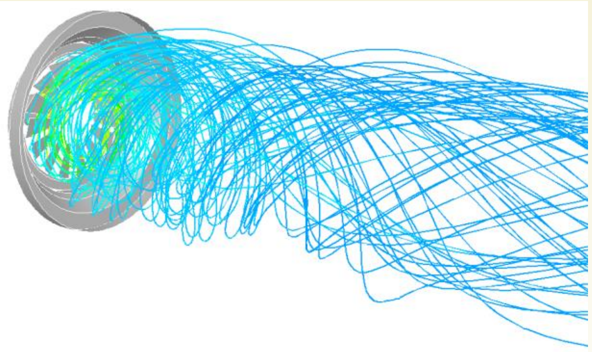




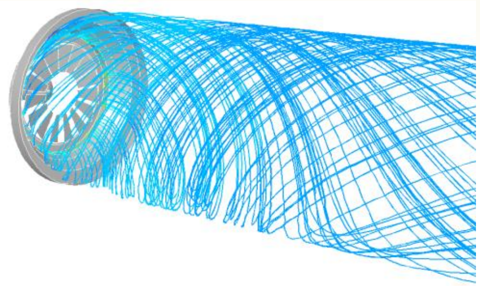
The three different flow path lines through the combustor:



core flow at the center of the burner



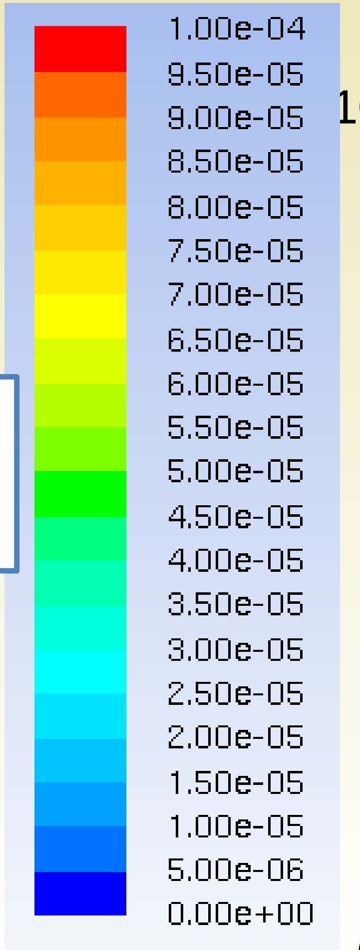
flow through the swirl vanes



flow the outer gap

Droplet diameter evolution reactive condition

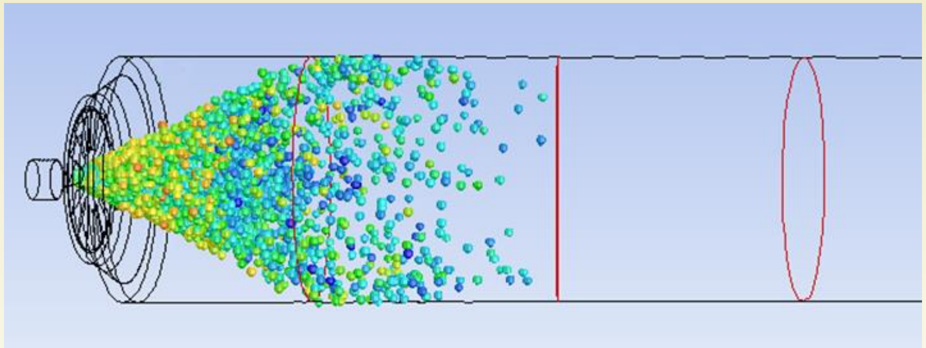
Droplet diameter (μm)



100μm

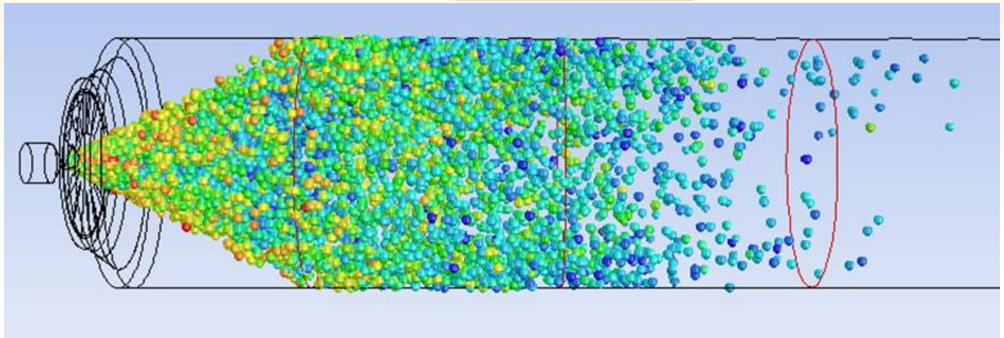
0

kerosene



evaporation process is slower for methanol

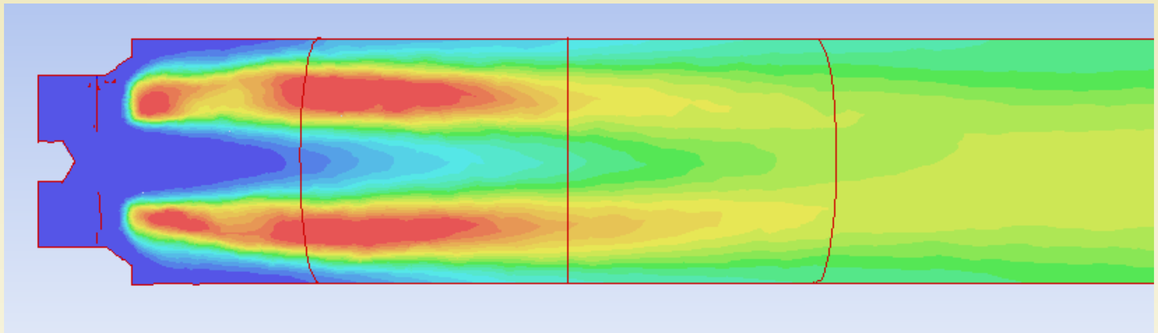
methanol



0.1 m 0.2m 0.3m

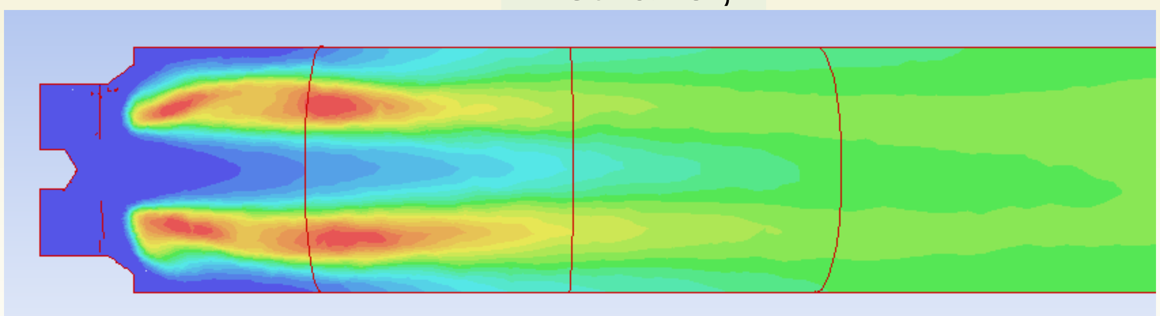
CFD results - Contours of total temperature

kerosene,

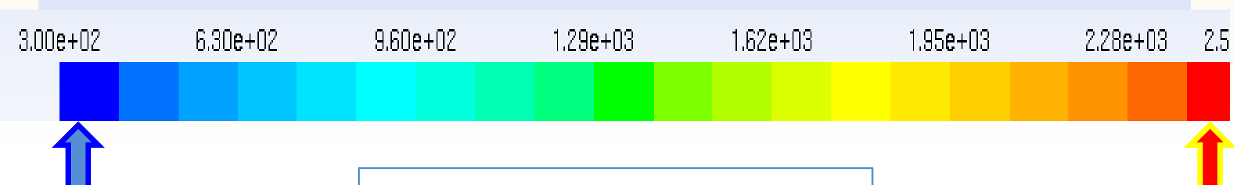


Kerosene
(Texit = **1493K**)

methanol,



methanol
(Texit = **1439K**)



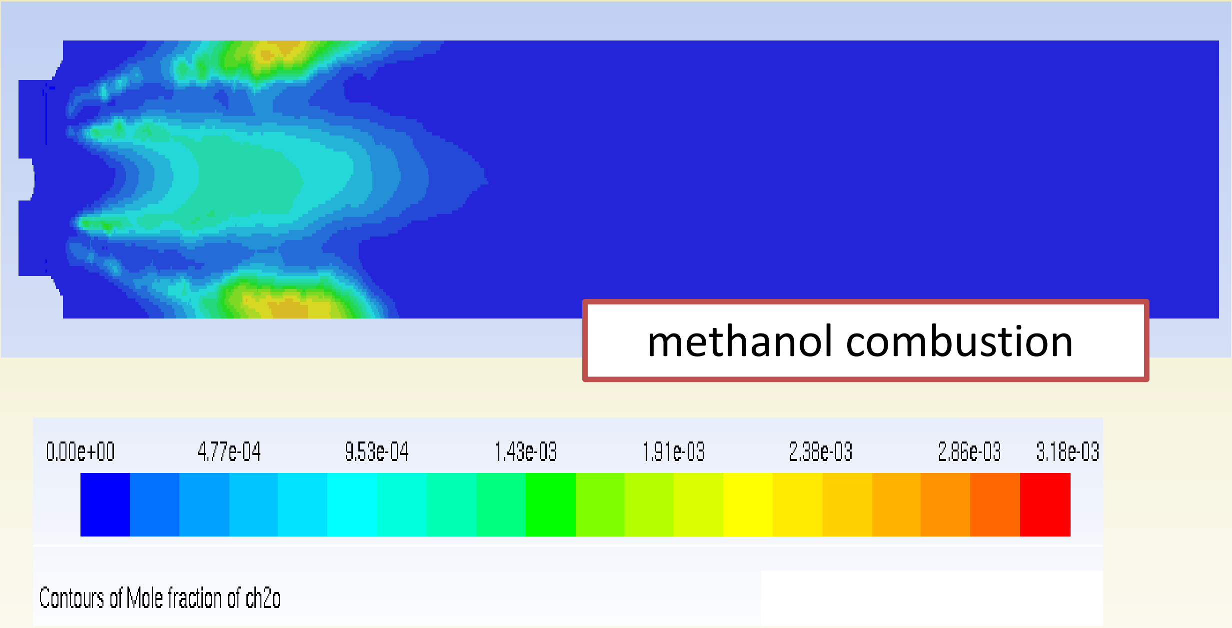
300K

Equal thermal power,
EDM, single global reaction.

2500K

INCOMPLETE METHANOL COMBUSTION (REQUIRES LONGER DISTANCE FOR COMPLETION)

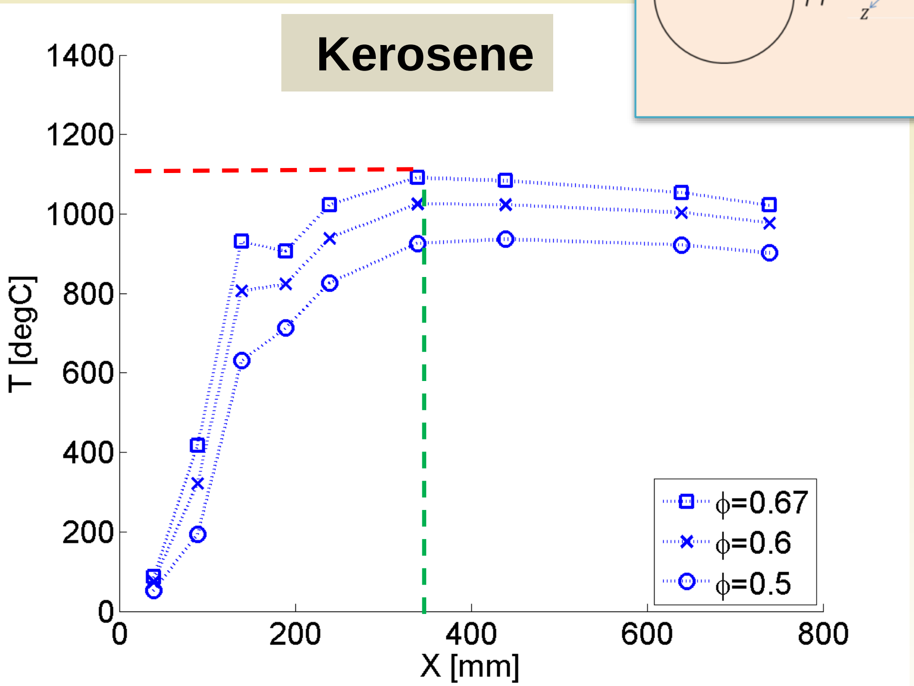
Mole fraction of formaldehyde

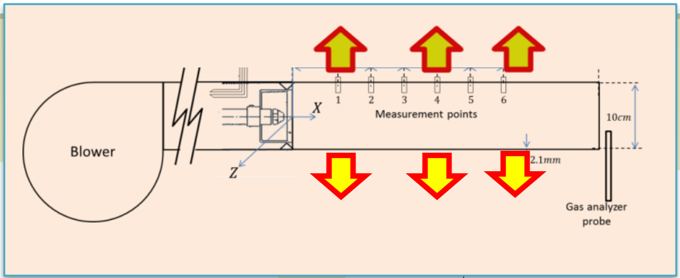


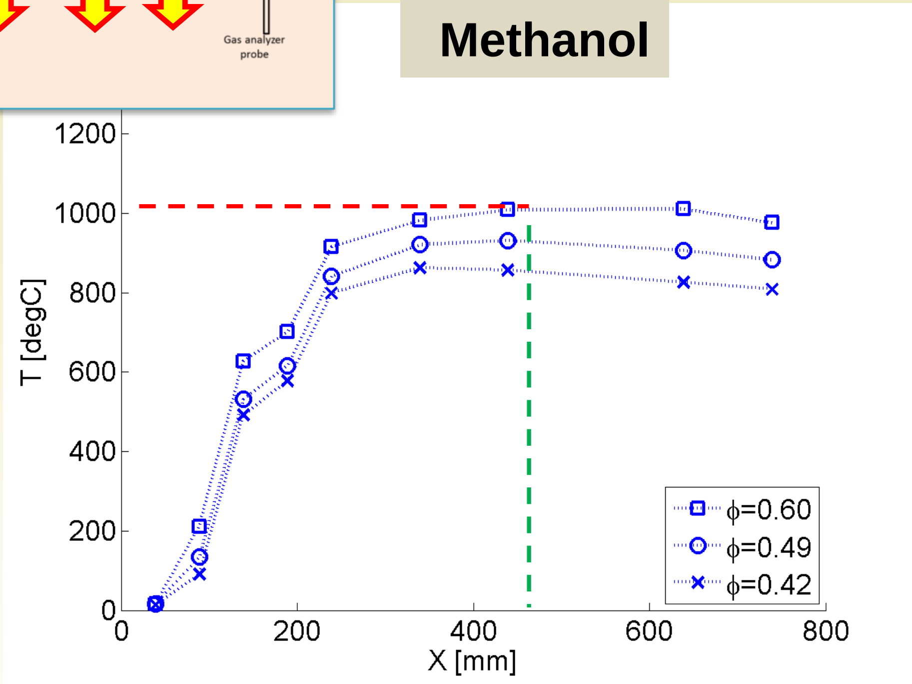
Combustion model: EDC (Li Mechanism - 18 species and 84 reactions)

(CH_2O max = 3178 ppm, CH_2O exit = 0.014 ppm)

Lengthwise temperature distribution (non insulated combustor)

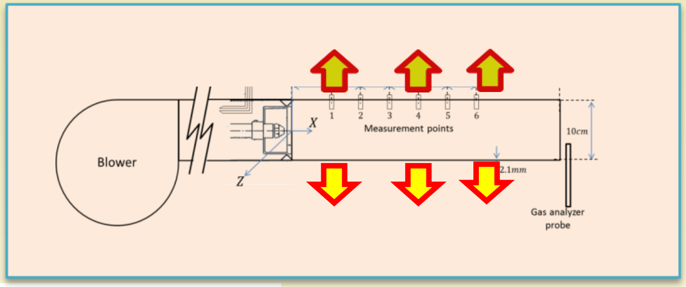




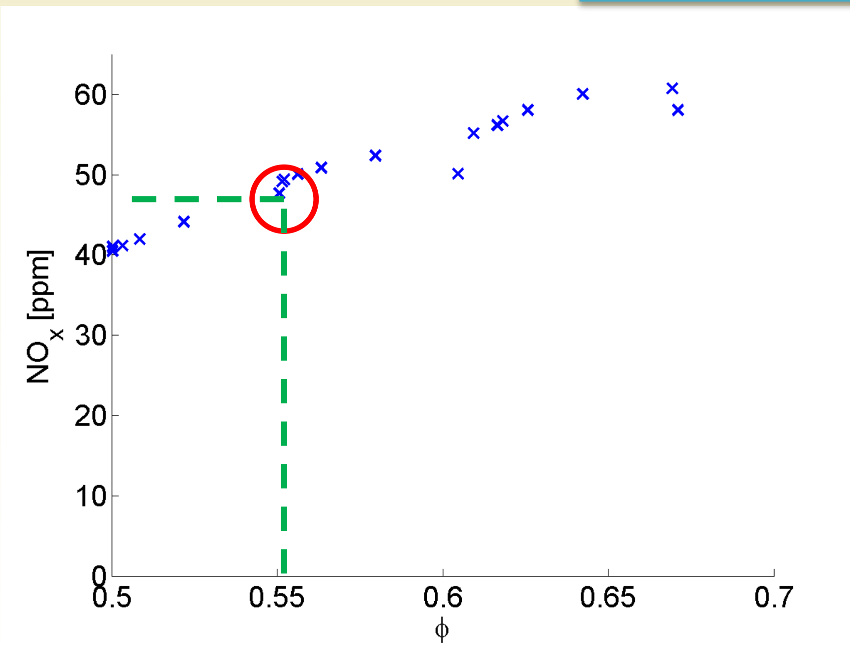


- Methanol has <u>larger fuel flow rate</u>, <u>longer evaporation</u> & <u>longer ignition delay.</u>
- Methanol flame is delayed and requires longer distances for its completion.

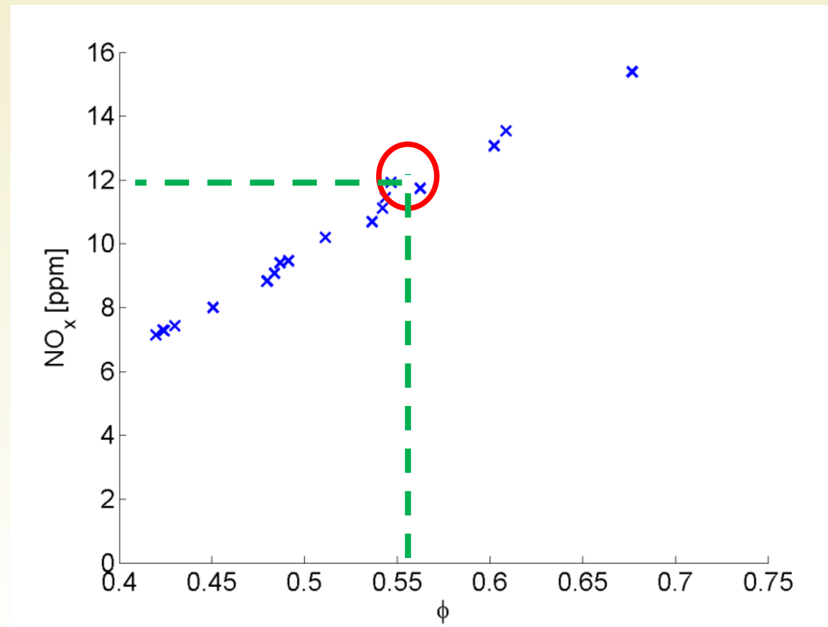
NOx concentrations [ppm] (@15%O2, non insulated combustor)



Kerosene

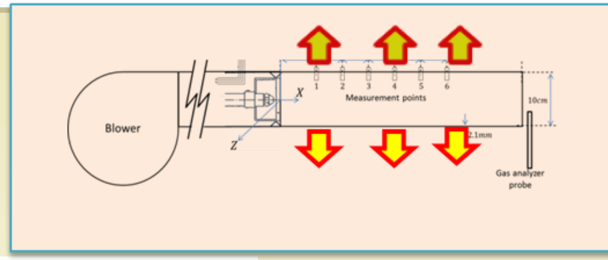


Methanol

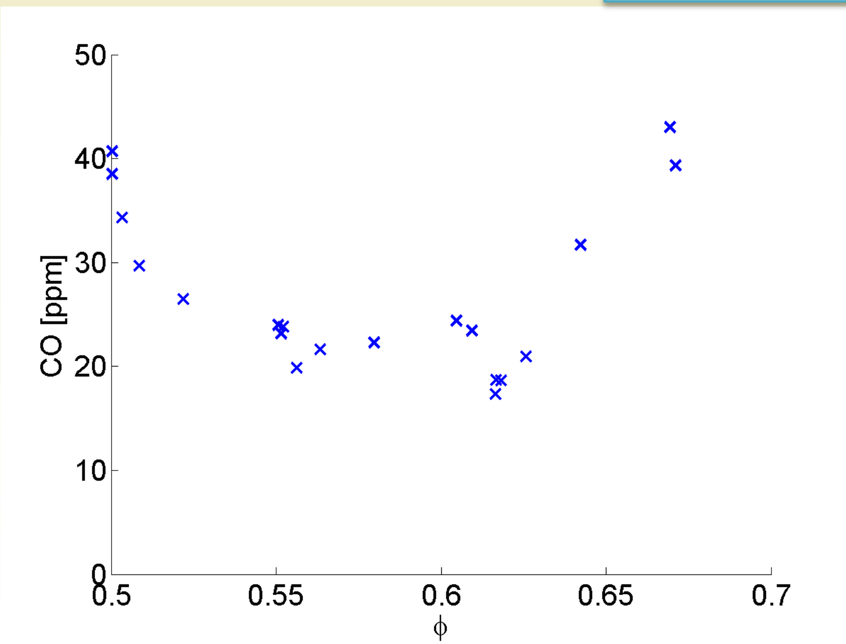


Due to lower combustion temperature, methanol combustion generates less NOx

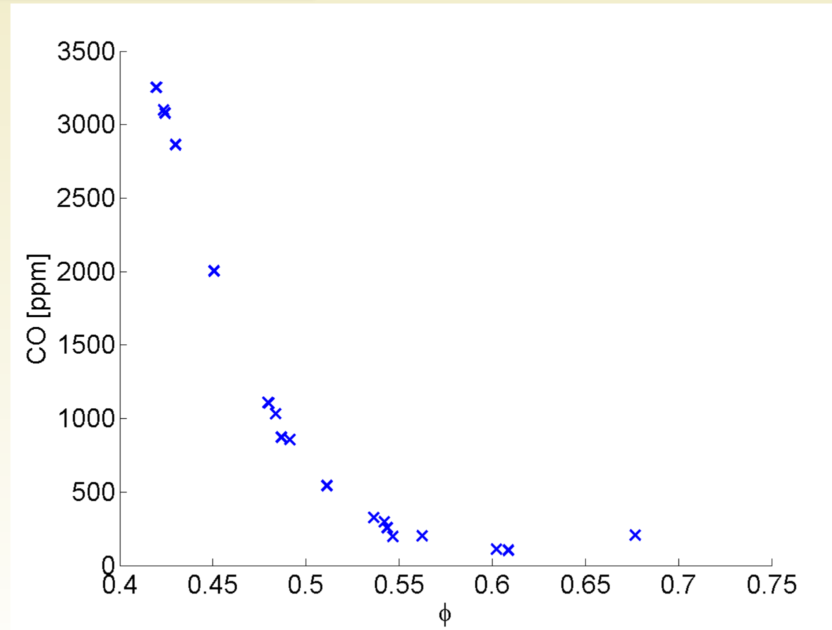
CO concentrations (@15%O2, non insulated combustor)



(a) Kerosene



(b) Methanol



Due to overall slower combustion process methanol requires larger distance to complete combustion

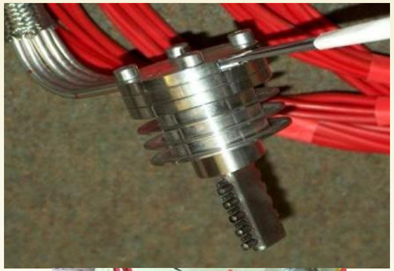
Results and conclusions (biojet Vs. kerosene):

- 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

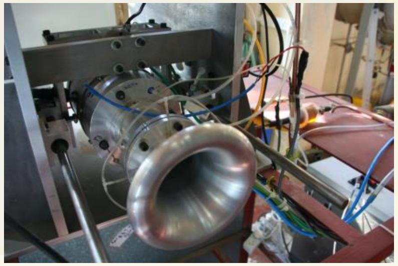
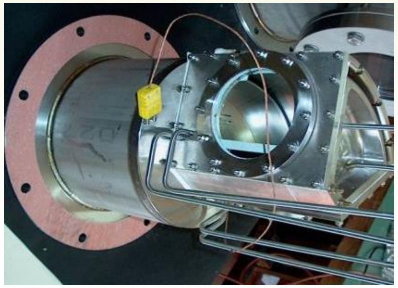
Results and Conclusions (biojet & methanol Vs. kerosene):

- 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 (CH_3OH).
- For equal thermal power, methanol liquid flow rate is higher, evaporation takes longer time and it has shorter ignition delay. A 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



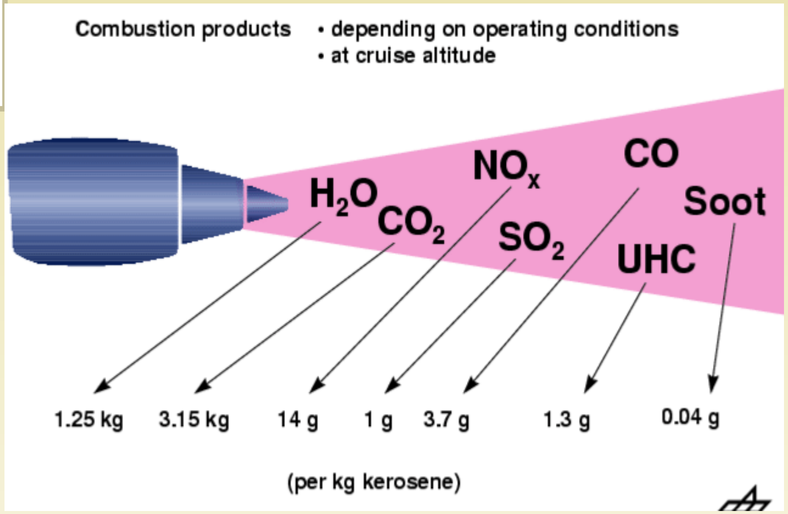



KEELING A FLAMEABLE IDEA

Climate assessment

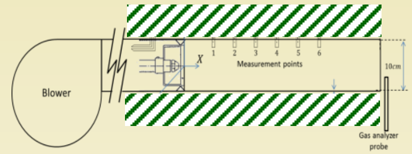
Climate is perturbed much differently by individual species.

Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

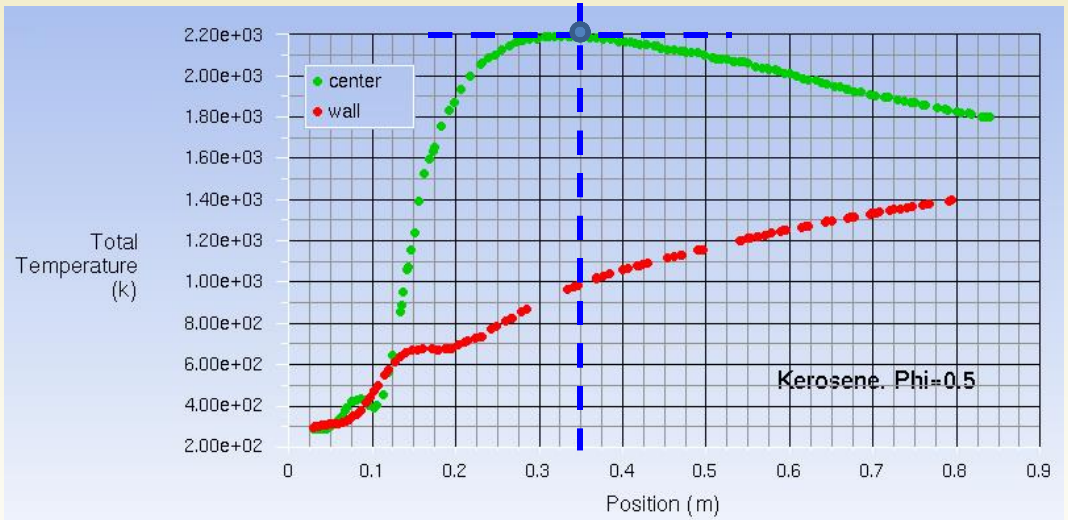


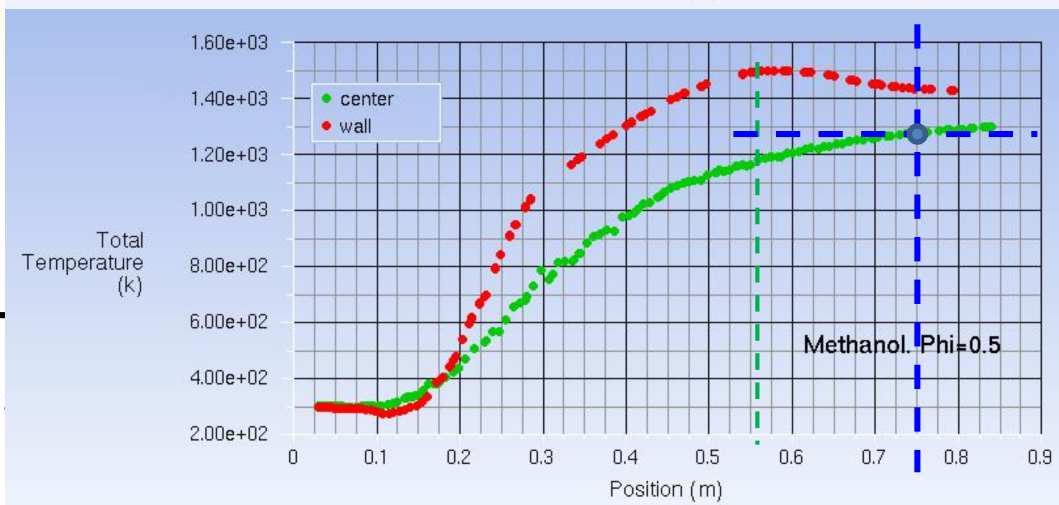
	CO_2	NO_x	Contrails	water vapour
Dependence on location	no	very	very	very
Perturbation lifetime	Decades	O_3 weeks (CH_4 months)	hours	Troposhere (0~10Km) - hours Stratosphere (10~50Km) – months
Climate impact	Decades	Decades	Decades	Decades

TEMPERATURE DISTRIBUTION ALONG THE COMBUSTOR TUBE (insulated combustor)

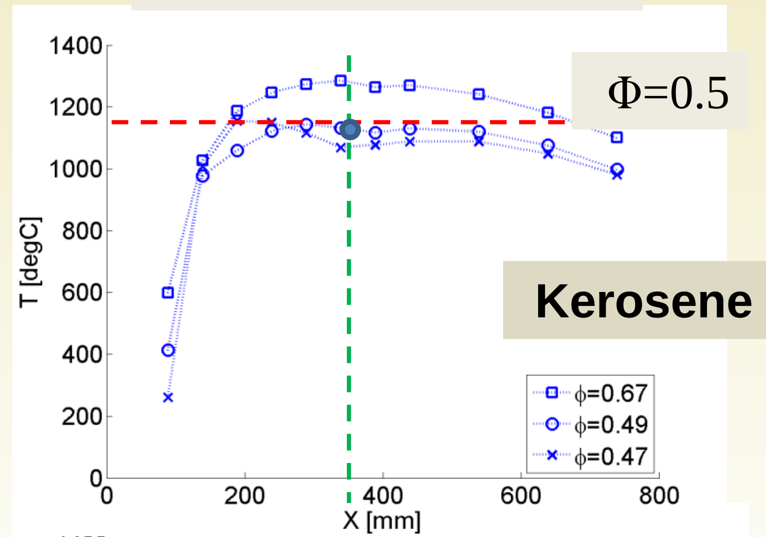


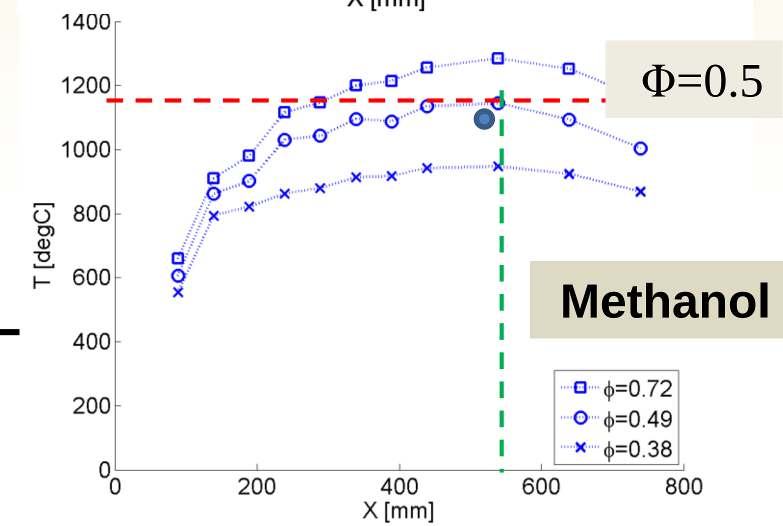
CFD SIMULATIONS





EXPERIMENTAL RESULTS

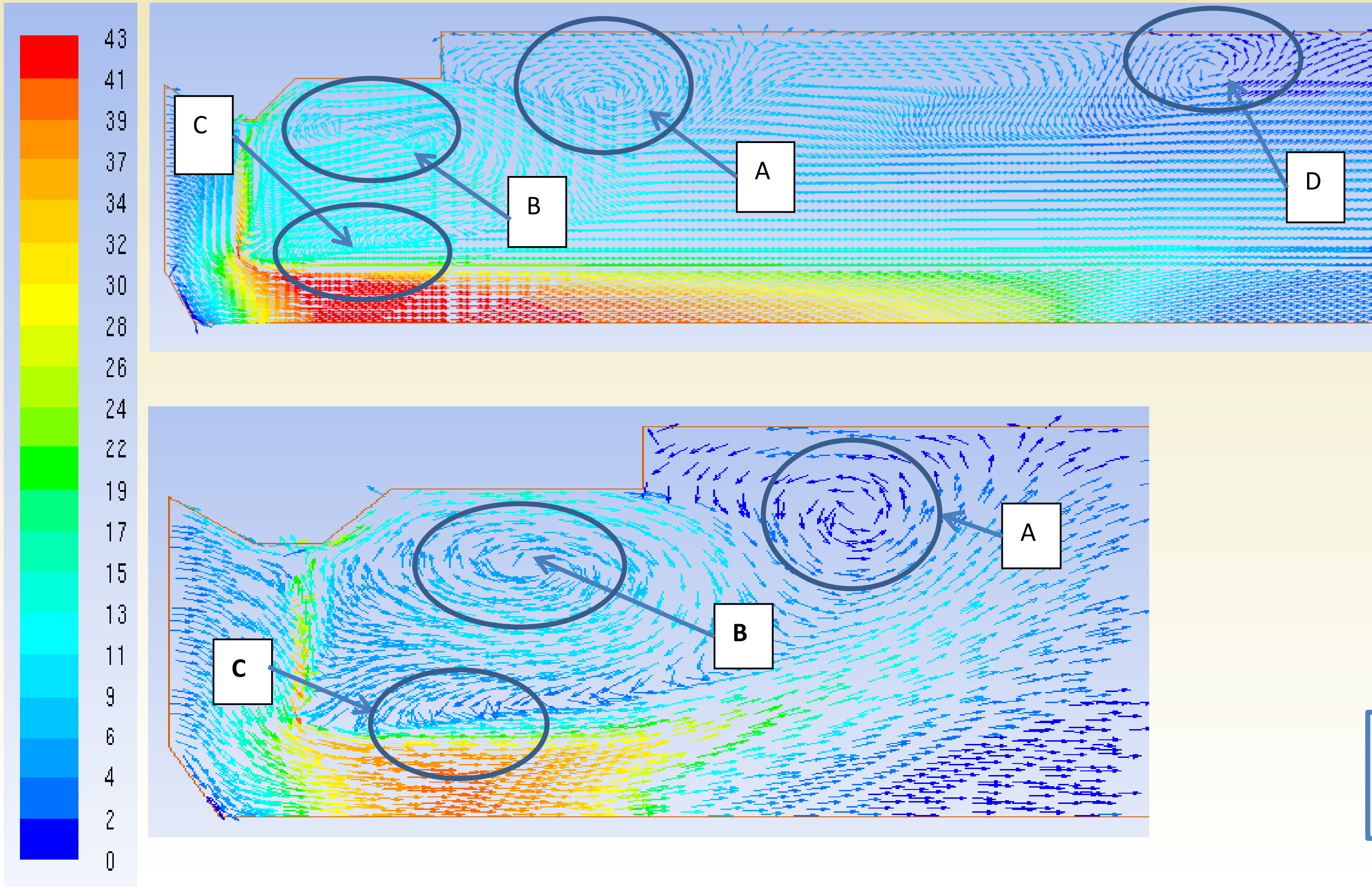




Kerosene and methanol comparison, summarized results
Equivalence ratio ER=0.61

Combustion Model	Wall Temp., K	T max, K	T, K (average exit)	NOx, ppm(exit)
CFD. Kerosene. Non-adiabatic	850	2404	1452	45.7
Experimental. Kerosene. Non-adiabatic	870	-	1430 (CORRECTED)	55
CFD. Methanol. Non-adiabatic	880	2340	1352	10.6
Experimental. Methanol. Non-adiabatic	823	-	1380 (CORRECTED)	9.5

"Cold" simulation results



1260000 cells

4 recirculation zones

2400000 cells

3 recirculation zones

11700000 cells

3 recirculation zones

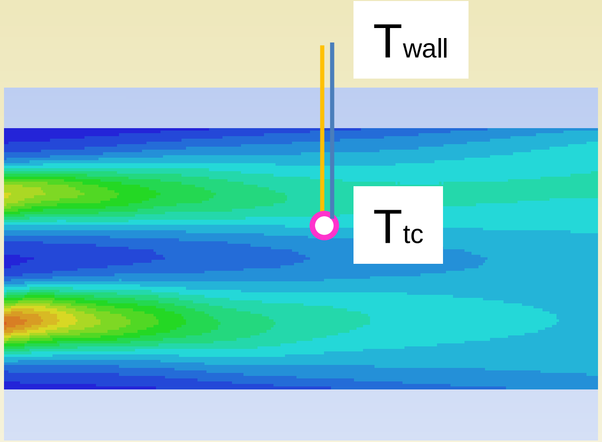
Recirculation zone moves

Velocity vectors colored by velocity magnitude, m/s

Actual temperature estimation from thermocouple reading

Heat (energy) balance

$$hA(T_g - T_{tc}) \approx \varepsilon\sigma A(T_{tc}^{\,4} - T_{wall}^{\,4}) \qquad (1)$$



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)*

$Re = V_g d_{tc}/\nu_g$

$\sigma = 5.7\cdot 10^{-8}\ {}^{Wm^2}/_{K^4}$

For our case

$V_g = 12m/s$

$d_{tc} = 3mm$

$Re = 183$ $\varepsilon = 0.9$

$\lambda = 0.12\ W/(m\cdot K)$ $Nu = 21.2$

$Nu = 21.2$ $T_{wall} = 943\ K$

$Pr_g = 0.57$ $T_{tc} = 1423\ K$

$Pr_{wall} = 0.65$

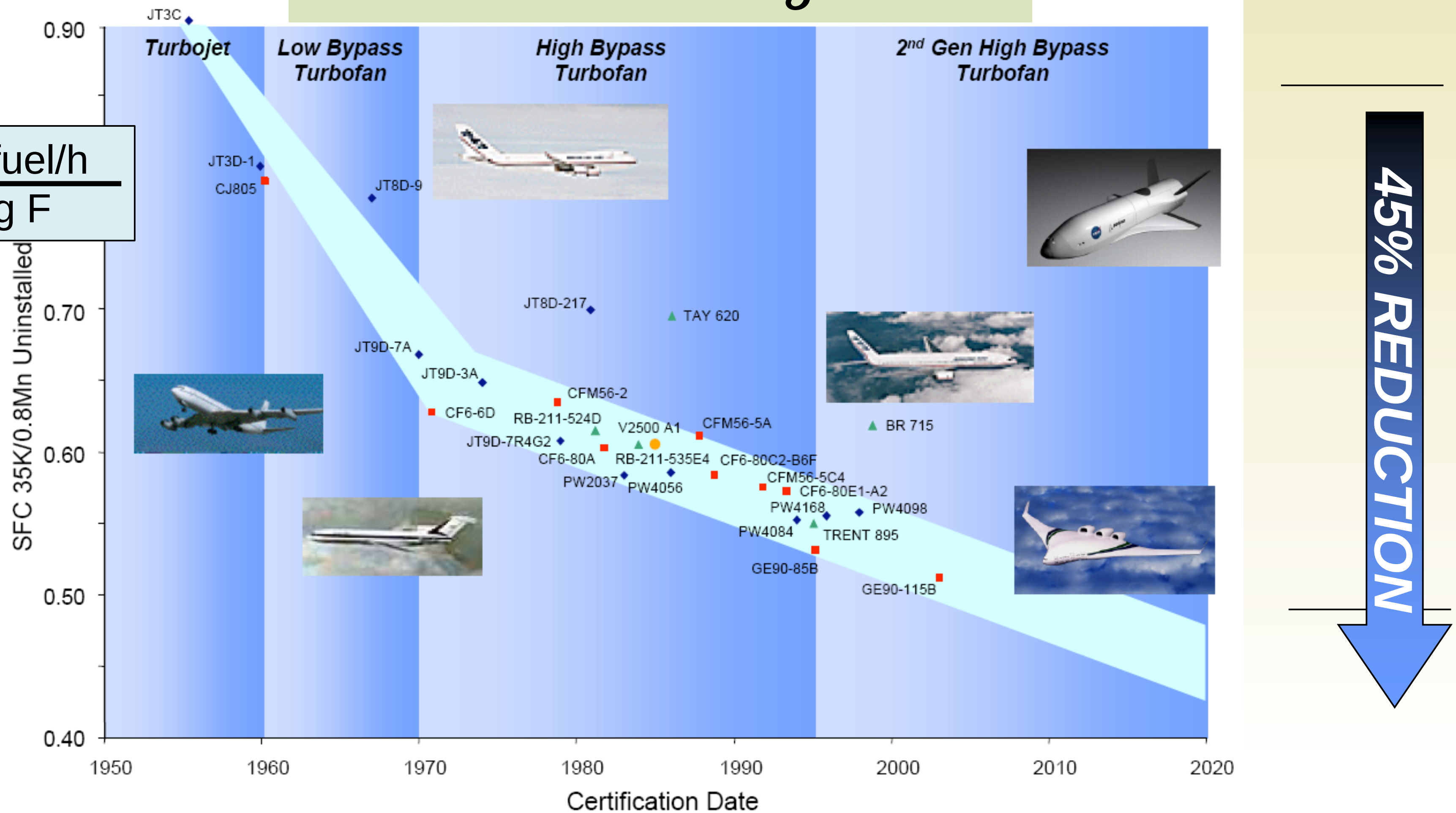
Solution of equation (1) gives

$$\boxed{Tg - Ttc \approx 199K}$$

Ref. : *I.L. Roberts et al. "Estimation of Radiation Losses from sheathed thermocouples", *Applied Thermal Engineering, 31 (2011), 2262-2270*

Performance Advancements

Evolution in Engines

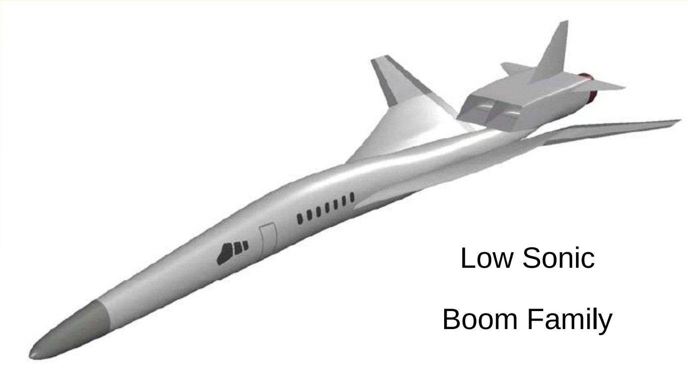


New Aircraft Concepts (noise, drag, payload, speed)

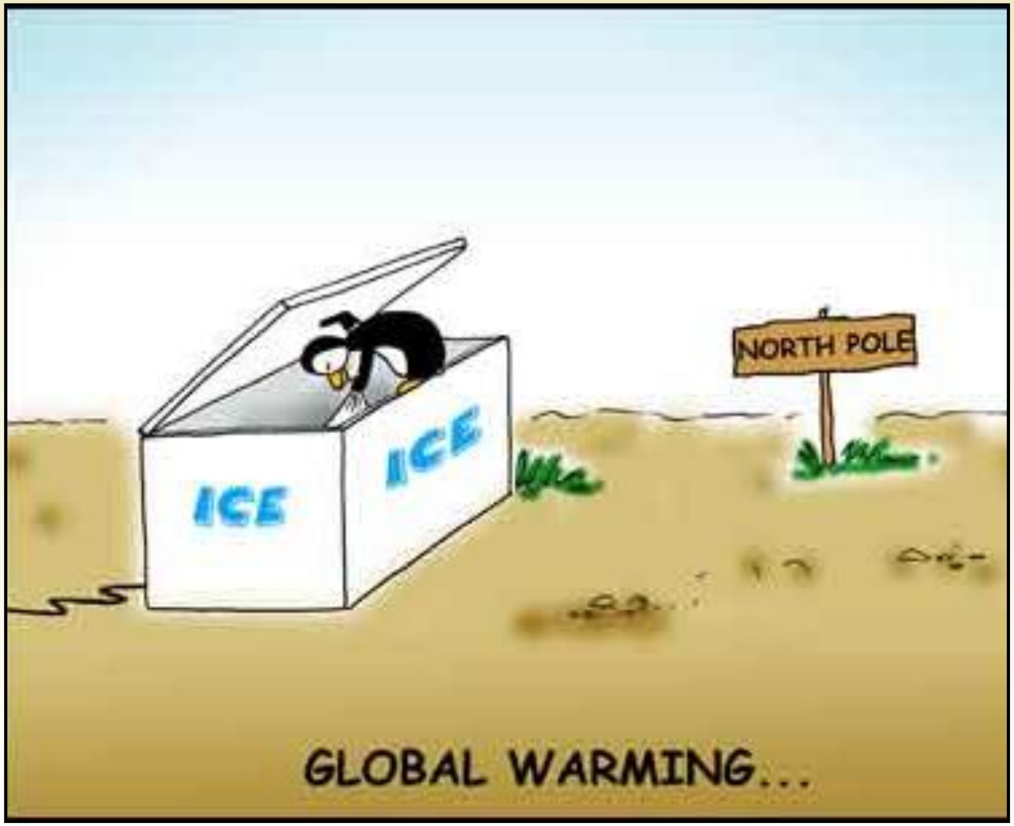
BLB configuration and
Contra Rotating Open Rotor

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

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



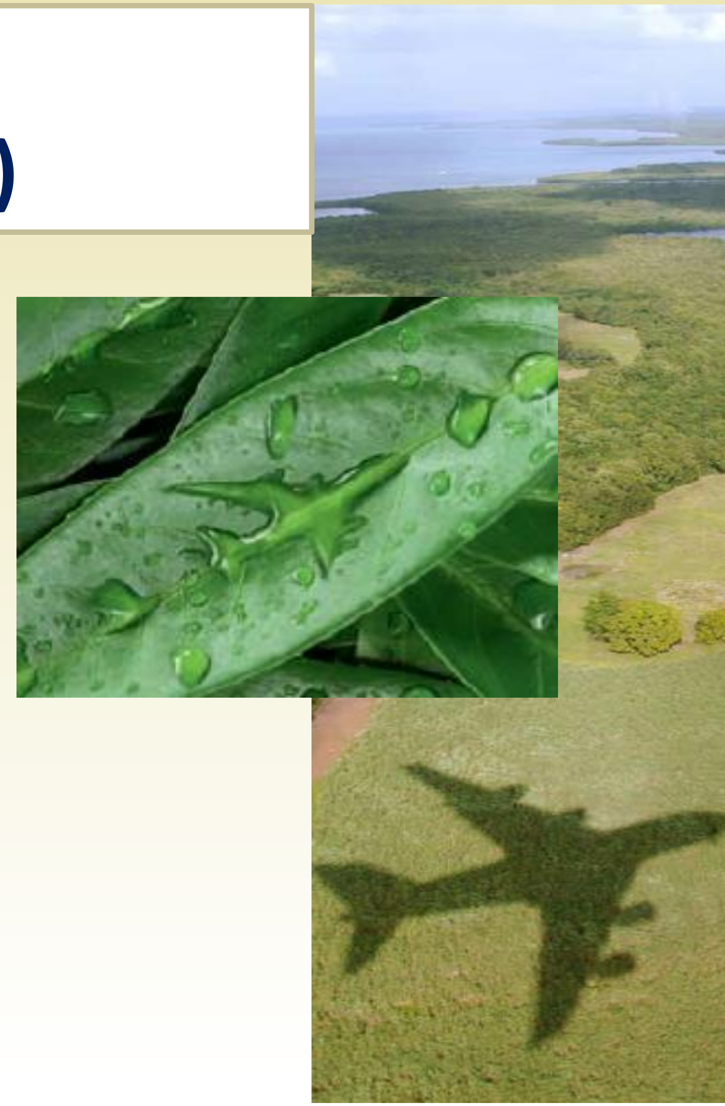
If we don't do any thing then….



Flight Path 2050 Vision, (propulsion perspective)

- 75% reduction in CO_2 emissions per passenger kilometre (cf. ATAG target).
- 90% reduction in NO_x 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 **X**TL (**G**TL, **B**TL, **C**TL)
  (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

07/2011: American Society for Testing and Materials (ASTM), International certifies blend of plant oil & animal fat

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)

Economic and Regulatory Issues

- Industrial production
- Worldwide availability
- Business case
  - Certification
  - ETS (Emissions Trading Scheme)