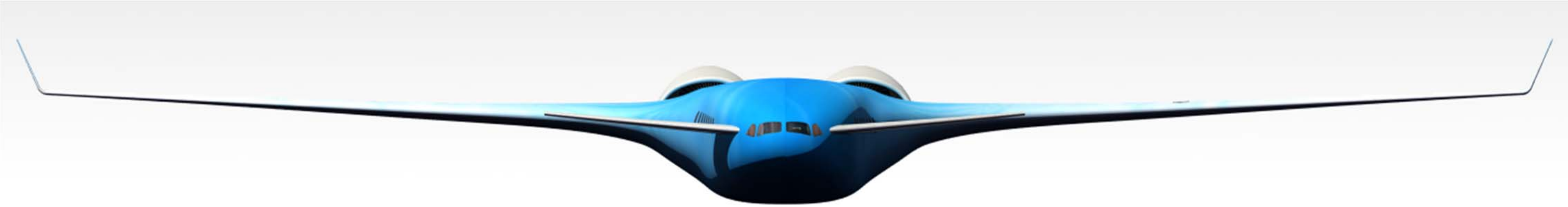

A Novel Hybrid Combustion System for Future Aircraft Engines

Combustion Research in the Netherlands: 19/3/2021

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Associate Professor
Flight Performance and Propulsion
Faculty of Aerospace Engineering
T.U. Delft

TU Delft

Contents

- Rationale for Sustainable Aviation
- Why Hybrid Combustion
- The AHEAD project
- The APPU Project
- Conclusions

The rationale for change…

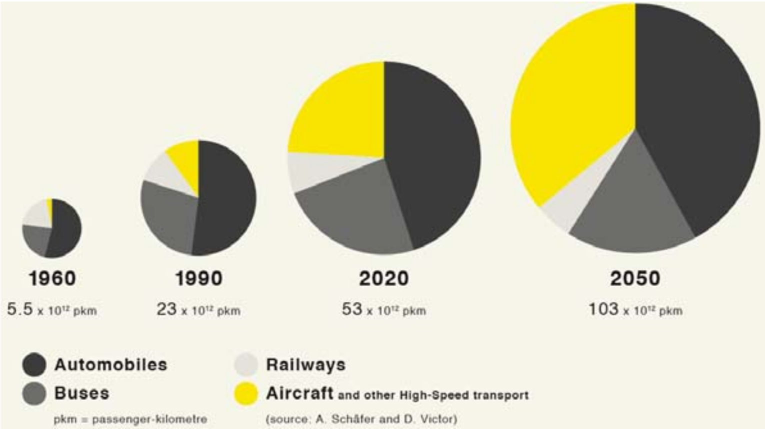
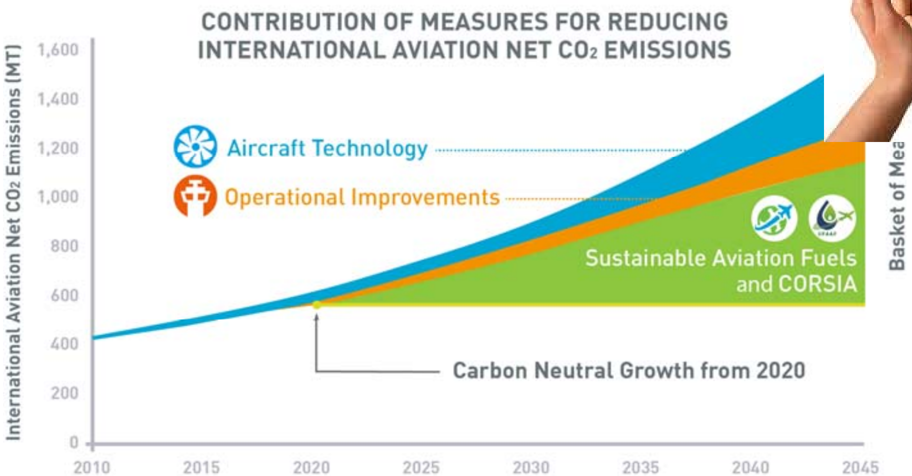
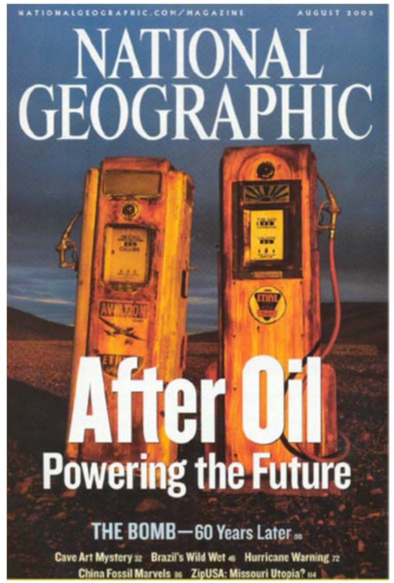


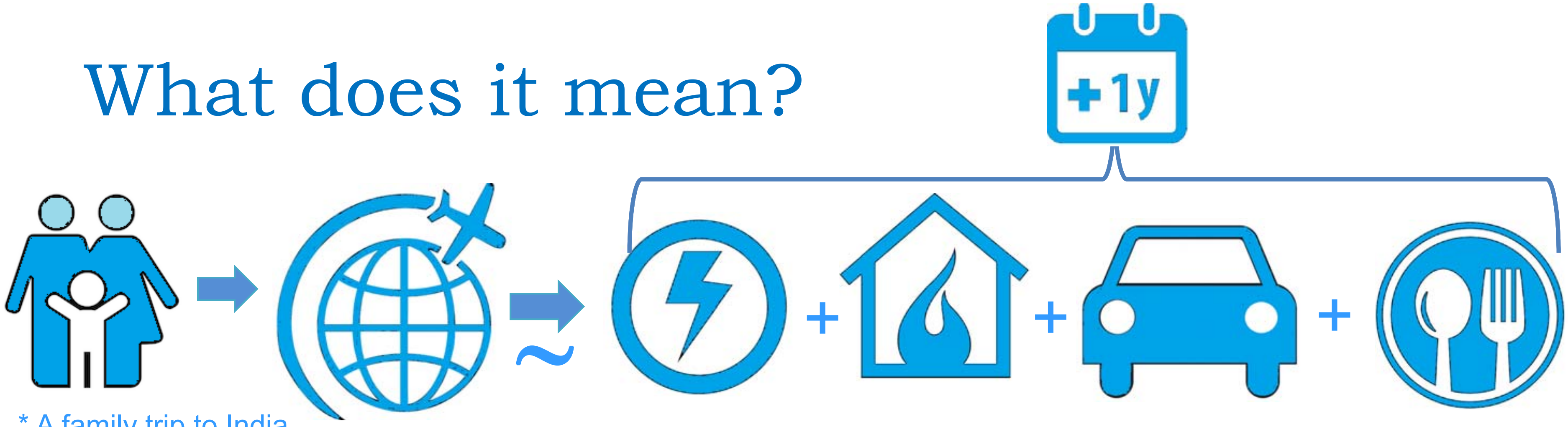
Fig. 1: Historical values and future prediction of transport volumes[1]

[1]The CleanEra Team, "CleanEra: a collection of research projects for sustainable aviation", 2015, IOS Press.

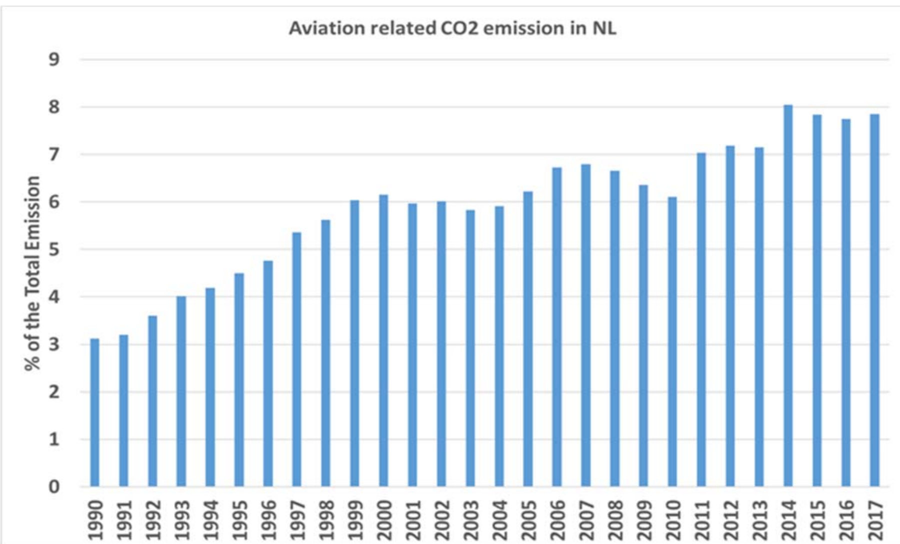




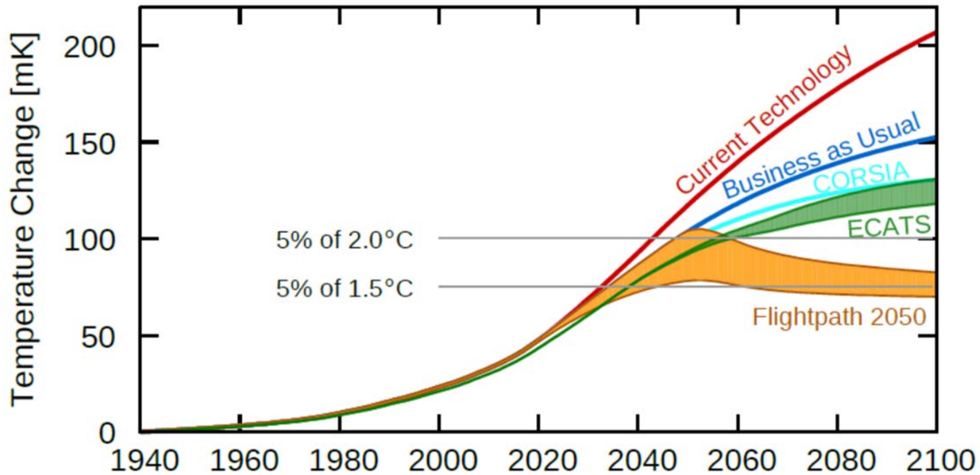
What does it mean?



* A family trip to India



Source: CBS, RHK



Grewe, V.,et al. . "Aviation climate impact and the Paris Agreement: targets, feasibility and COVID- 19 effects", **Nature Communications**

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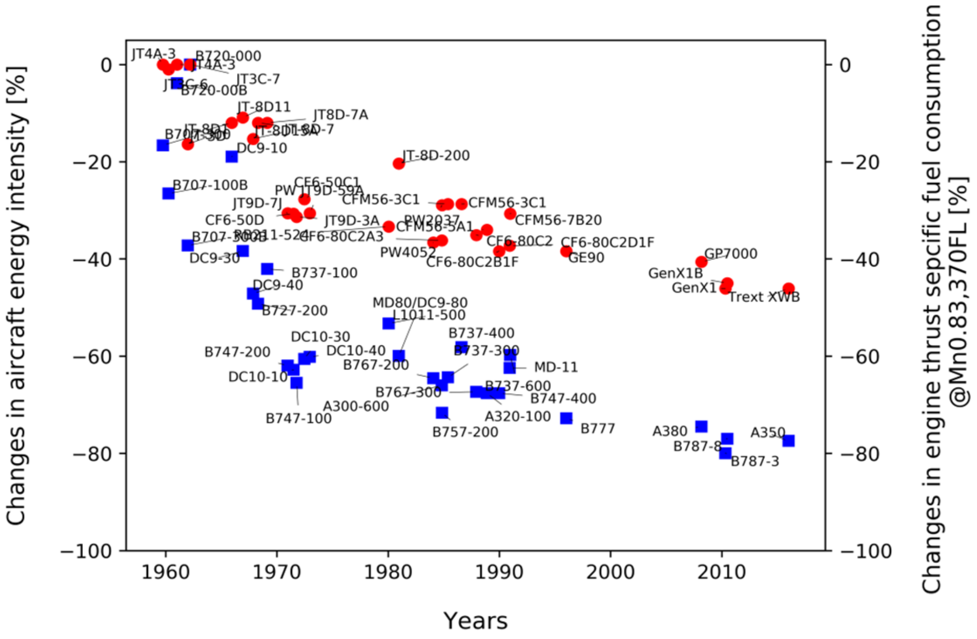
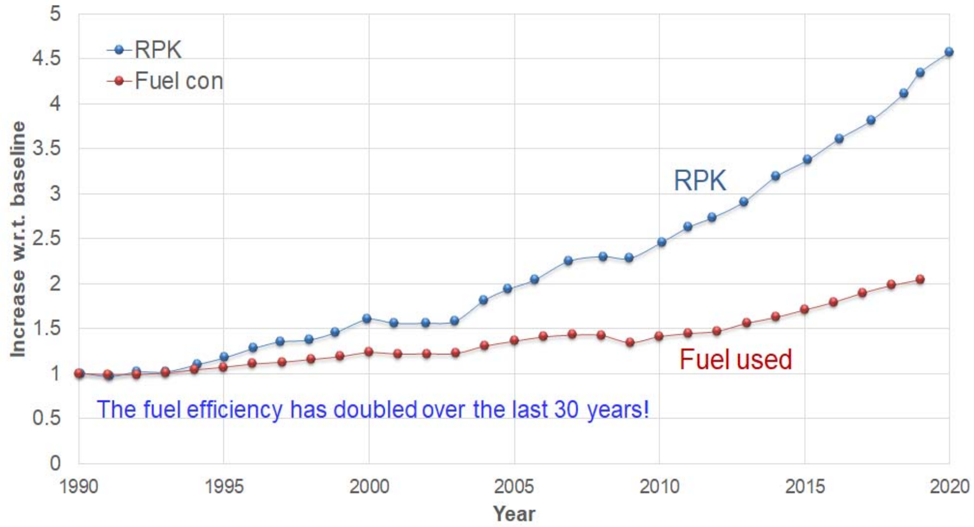
Improvement in aircraft fuel burn



F. Yin & A. Gangoli Rao "A Review of Inter-stage Turbine Burner Turbofan Engine Concept for Future Civil Aviation" Progress in Aerospace science, Vol. 121, 2020



A. Gangoli Rao, F. Yin, and H. Werij, "Energy transition in aviation: the role of cryogenic fuels", Aerospace, Vol.7 (12), pp.181, 2020.

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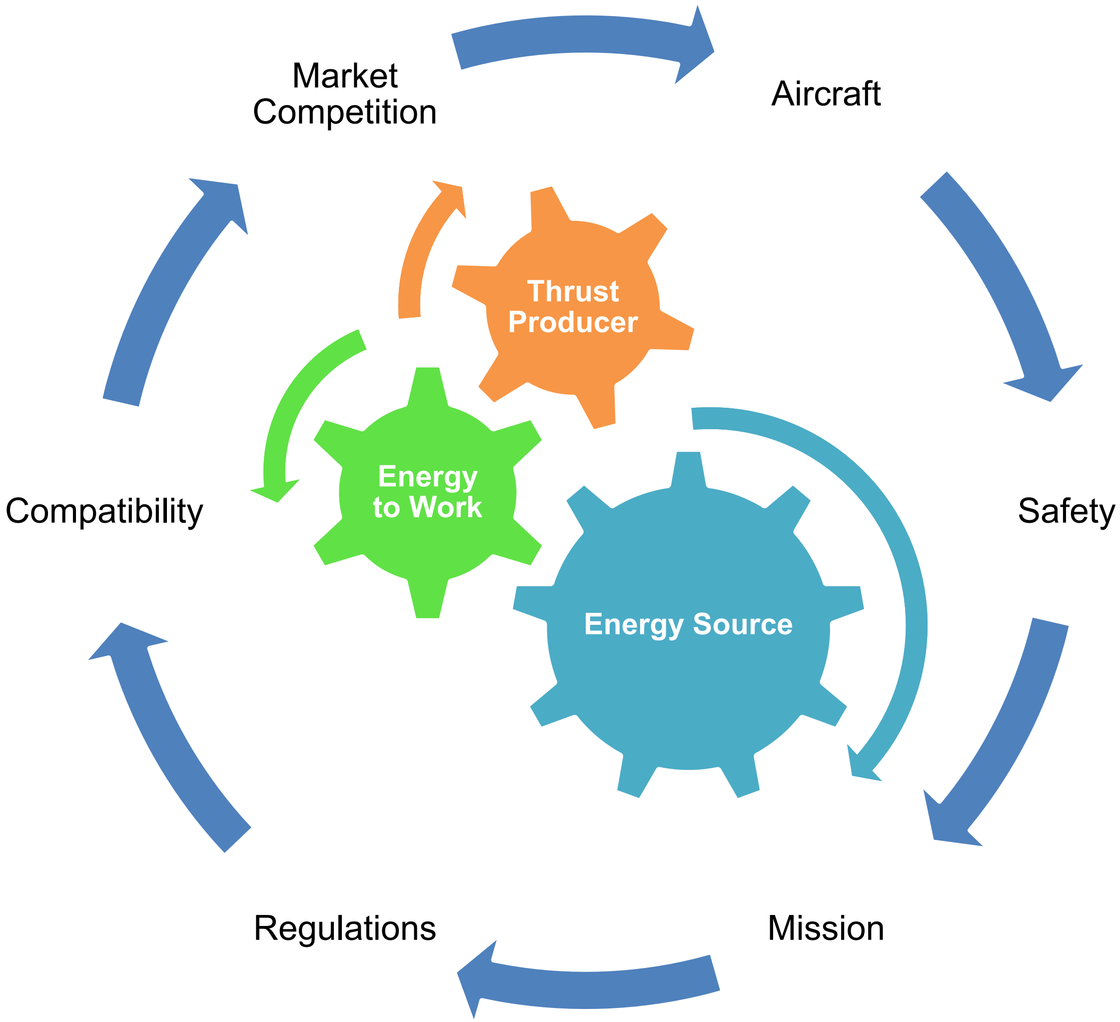
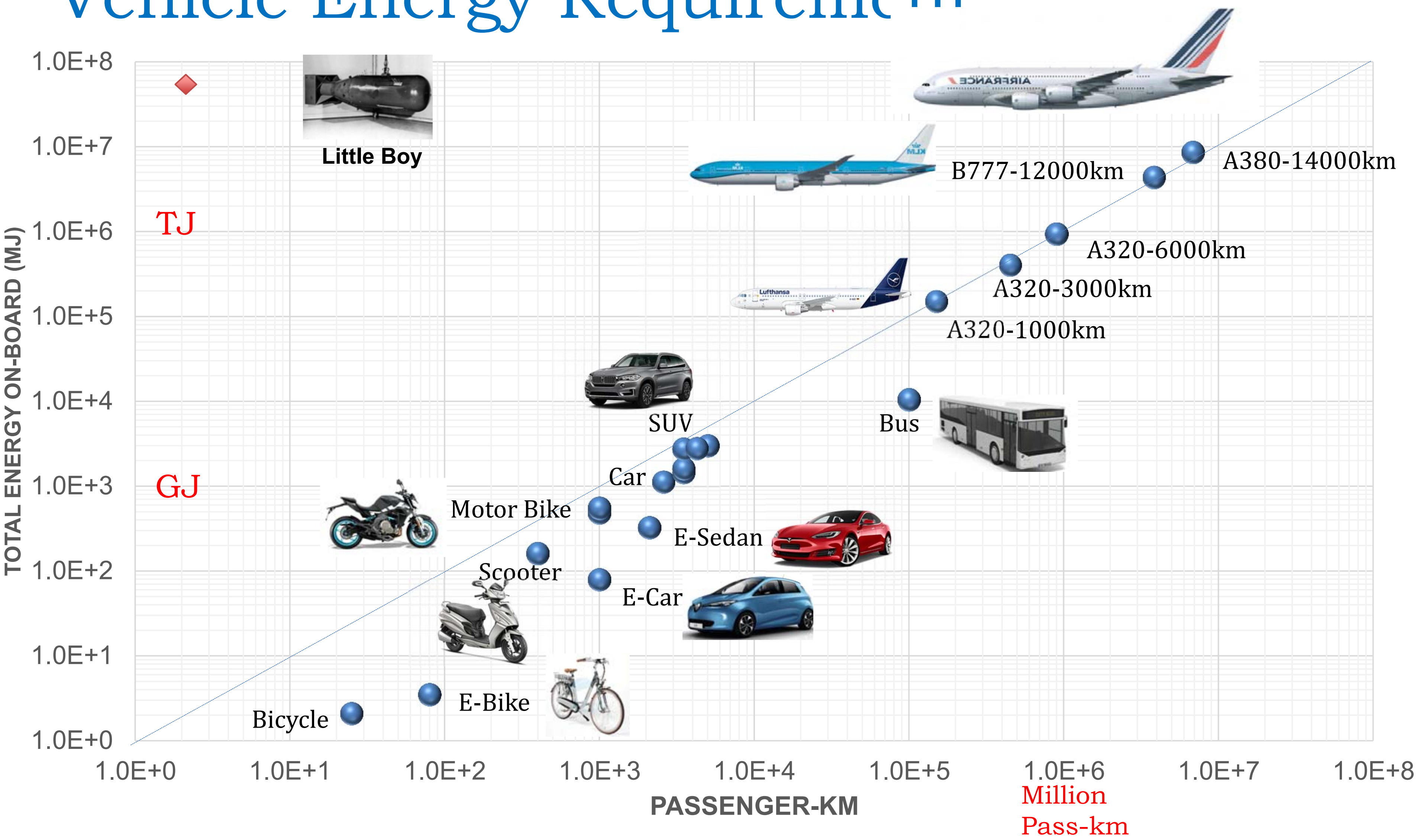
Elements of a propulsion system



Vehicle Energy Requirement



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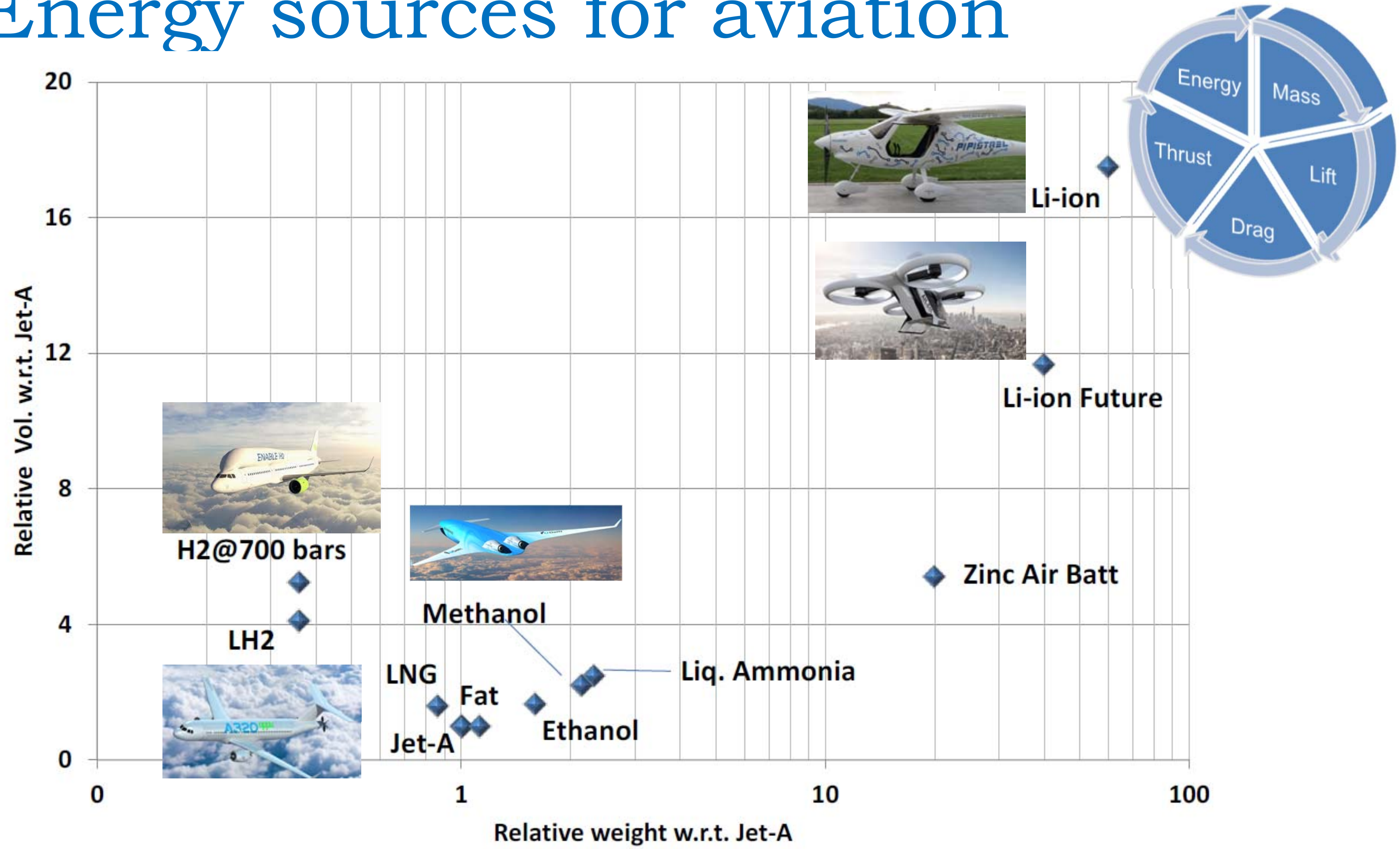
Energy sources for aviation



"No fuel is cheap when you have to make it yourself" -Prof. G. Eitelberg

A. Gangoli Rao, F. Yin, and H. Werij, "Energy transition in aviation: the role of cryogenic fuels", Aerospace, Vol.7 (12), pp.181, 2020.

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A Simplistic Overview

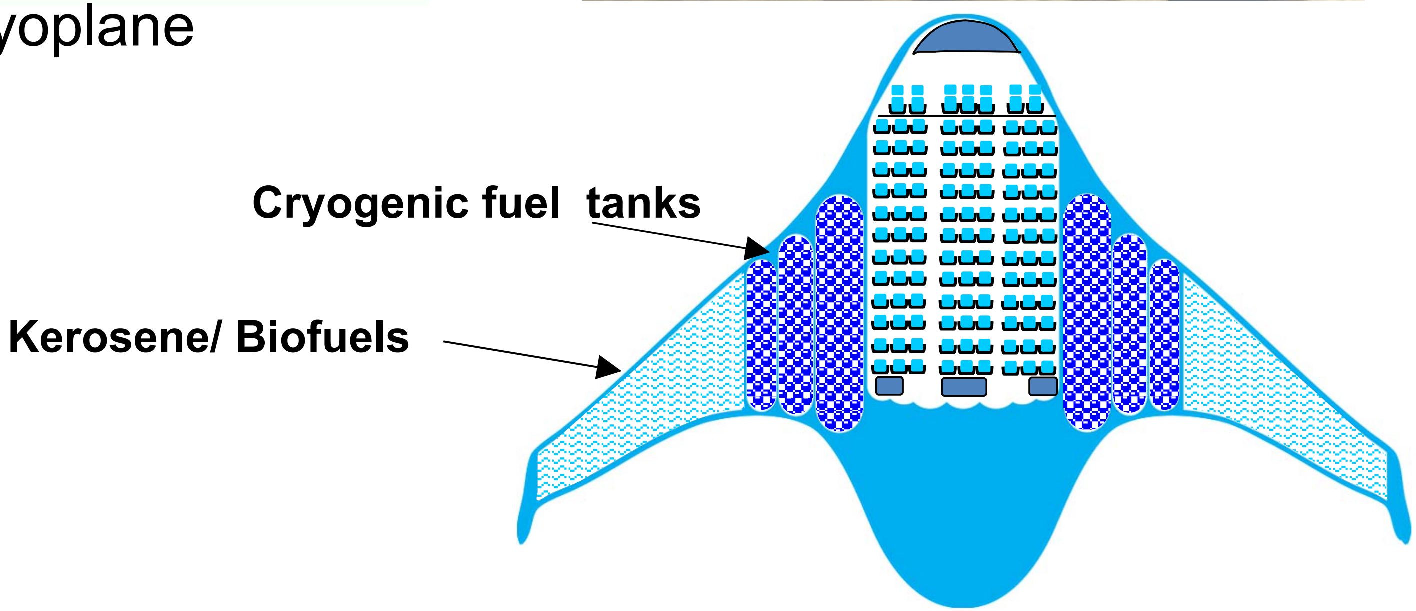
Parameter	Kerosene	Biofuel	Syn-Ker	Batteries	LNG	LH2
Energy Density	+	+	+	- -	+	+ +
Vol. Density	+ +	+ +	+ +	[illegible]	+/-	-
Emissions	- -	+	+	+ +	+	+
Cost	+ +	-	[illegible]	+	+ +	-
Availability	+ +	[illegible]	- -	[illegible]	+	+/-
Infrastructure	+ +	-	[illegible]	+/-	+	-
Safety	[illegible]	+	+	-	+/-	- -
Compatibility	+ +	-	+ +	-	+/-	-
Policy	-	+	+	+	+/-	+
Climate Impact	- -	+	+	+ +	+	+
TRL	9	8	6	5	4	3

None of the fuel meets all the criteria

Energy Mix is important

Storing Cryogenic Fuels

Cryoplane



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The consortium

- Delft University of Technology
- Pratt & Whitney Reszov, Poland
- Technical University of Berlin
- DLR, IAP
- Israel Institute of Technology-Technion
- Ad Cuenta b.v.

Advisory Board

- MTU Aero Engines
- EASA
- KLM
- Airbus Group Innovations

Dr. Feijia Yin

Dr. A. Perpignan

Ir. R. Sampat

Dr. A. Bhat

Dr. C. Huo

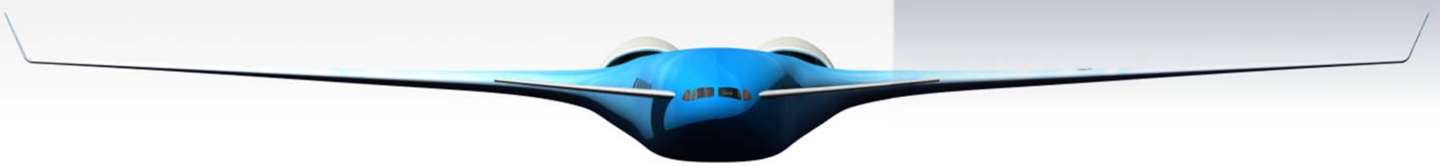
Dr. D. Dewanji

http://www.ahead-euproject.eu/

The Multi-Fuel BWB Aircraft

Multi-fuel: Cryogenic (LNG) and Liquid fuel (Kerosene/Biofuel)

- **Approx. 300 passengers**
- **Range: 14,000 km**



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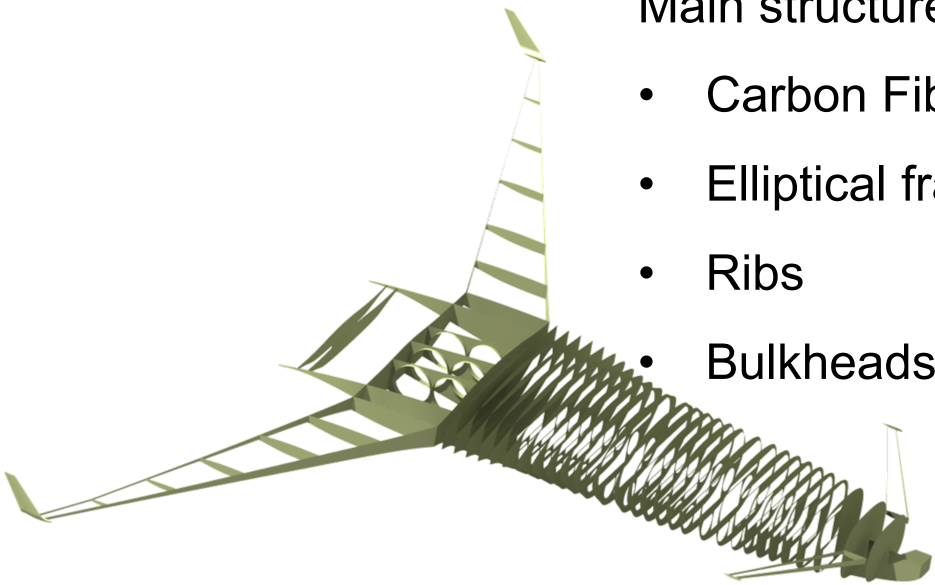
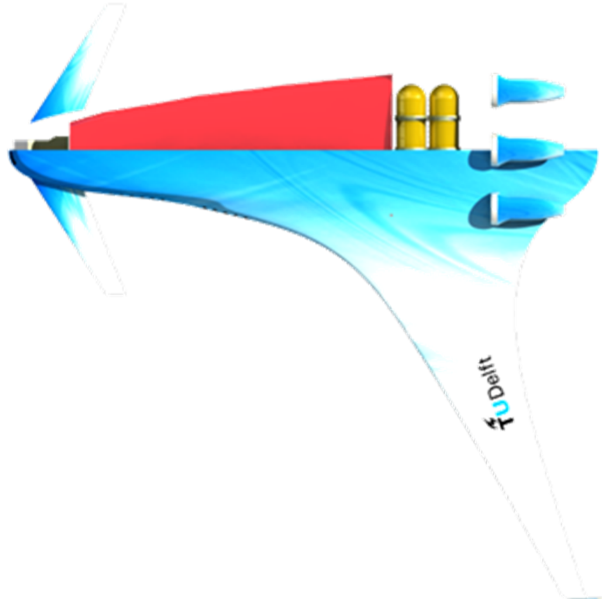
AHEAD
ADVANCED HYBRID ENGINES FOR AIRCRAFT DEVELOPMENT

Some details…

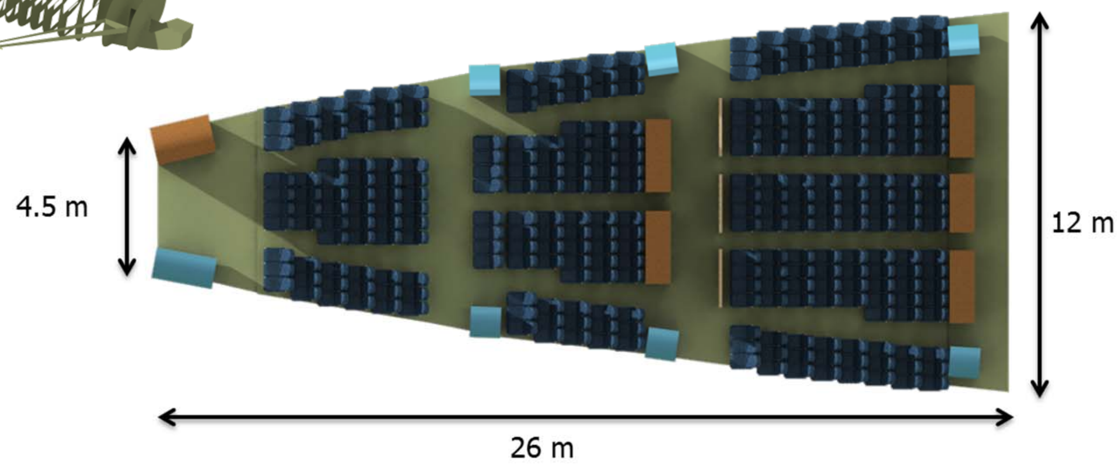


Main structure

- Carbon Fibre
- Elliptical frames
- Ribs
- Bulkheads



- 302 seats
- 8 lavatories and 7 galleys
- 6 Type-A emergency exits



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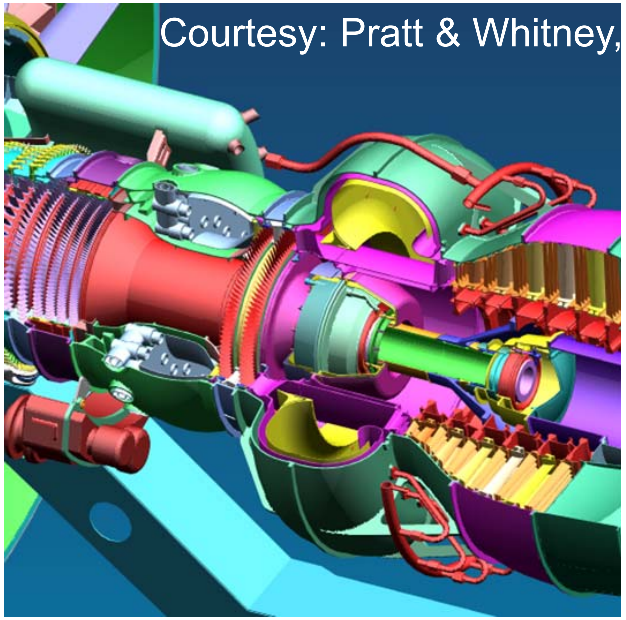
Hybrid Engine



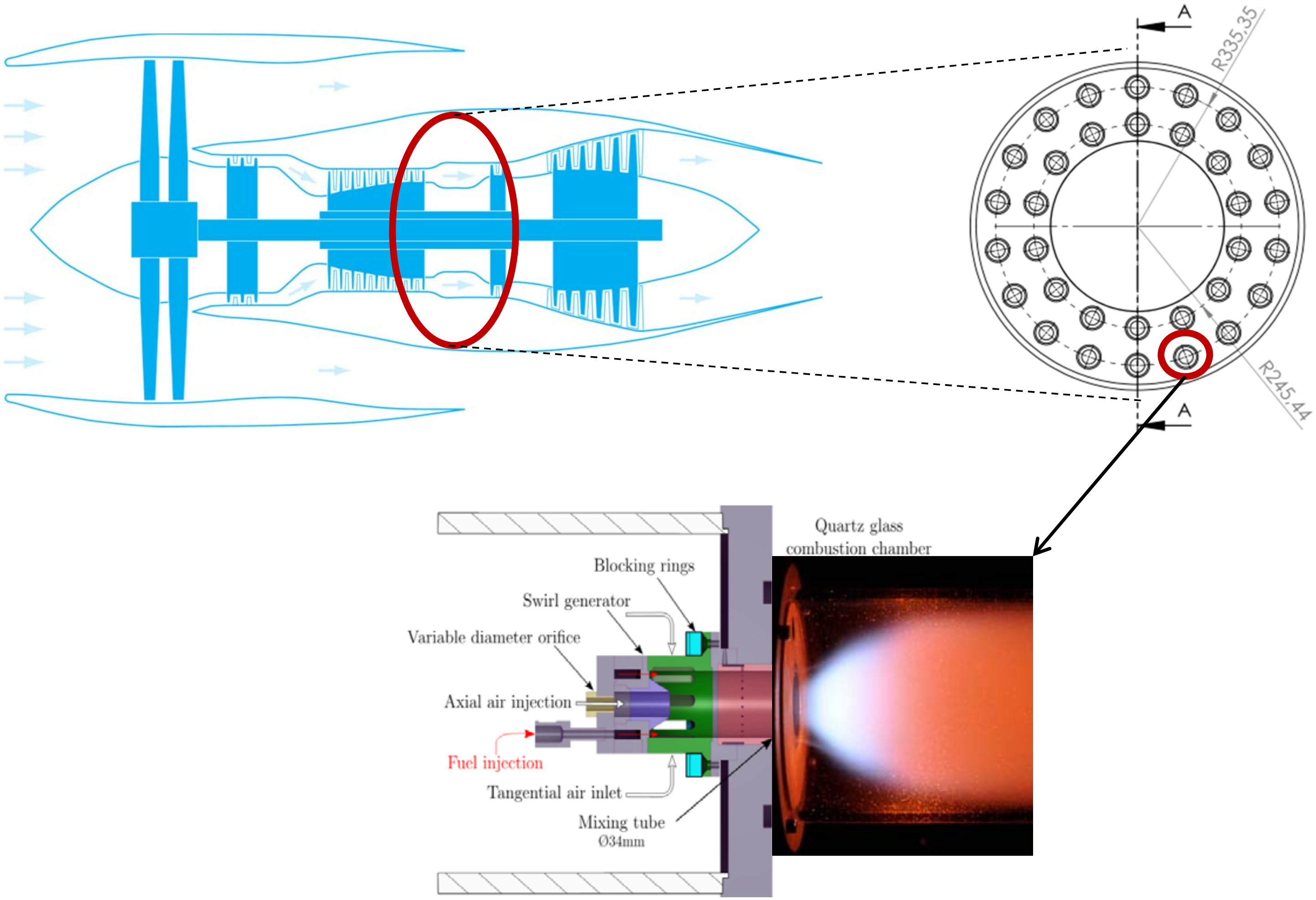
- LNG/ LH_2 Main Combustor
- Inter Turbine Flameless Combustor
- Bleed cooling by LH_2/LNG
- Counter rotating shrouded fans

Comparison with Boeing 777-200ER

- LNG/LH_2 used as fuel.
- CO_2 emissions reduced by 50 - 80%.
- Substantial NOx reduction expected > 80%

- Yin, F. & Gangoli Rao, A. "Performance Analysis of an Aero Engine with Interstage Turbine Burner", *The Aeronautical Journal*, Vol. 121, pp. 1605-1626, 2017.
- Yin, F. and Gangoli Rao, A., "A Review of Gas Turbine Engine with Inter-stage Turbine Burner", *Progress in Aerospace Sciences*. 2020, Vol. 121, pp. 100695, 2020.

The H_2 combustion chamber



Thoralf Reichel & Oliver Paschereit –Chair of Fluid Dynamics– TU Berlin

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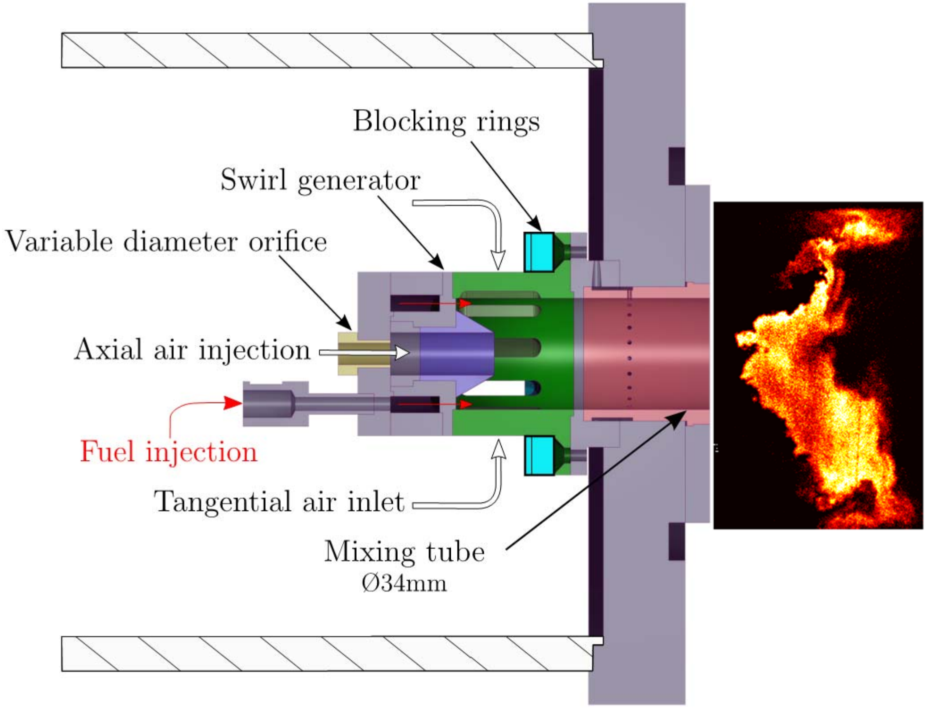
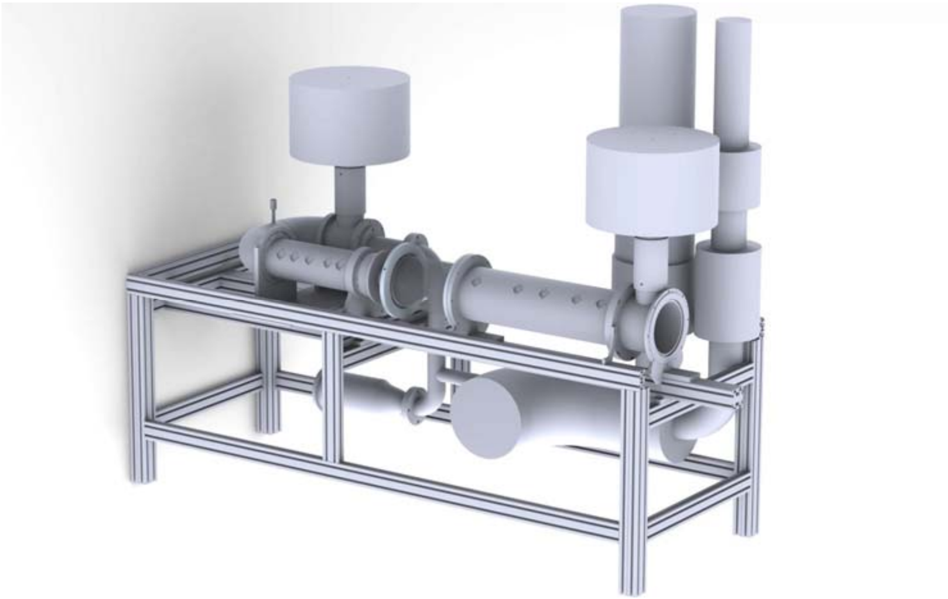
The premixed H2 combustor

Gas-fired tests with 100% hydrogen with axial injection on the TUB combustion test trig



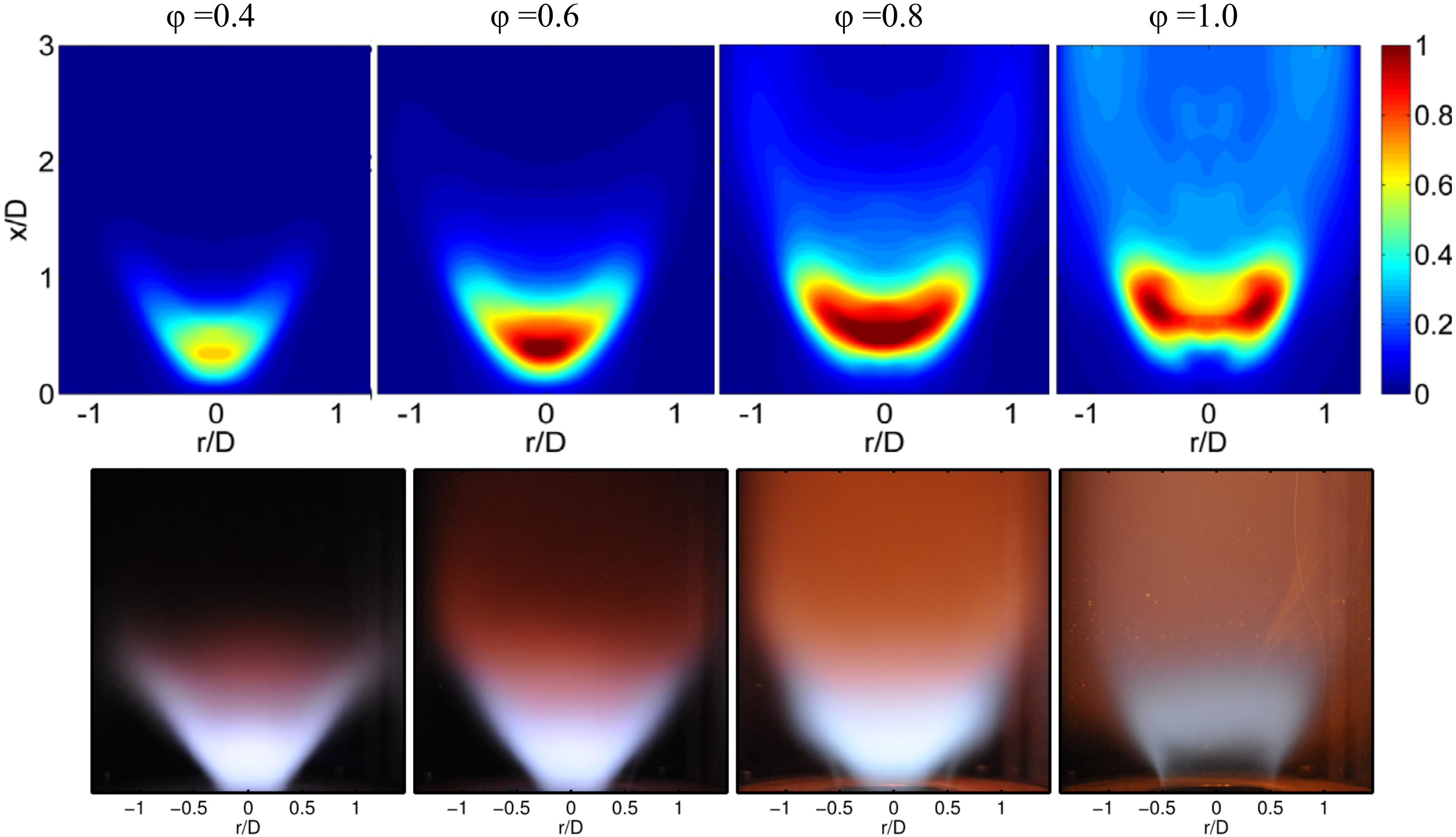


Reichel, T. G.; Terhaar, S. and Paschereit, C. O., "Increasing Flashback Resistance in Lean Premixed Swirl-stabilized Hydrogen Combustion by Axial Air Injection", Proc. of the ASME Turbo Expo 2014

Gas Fired Tests – Heat Release Images

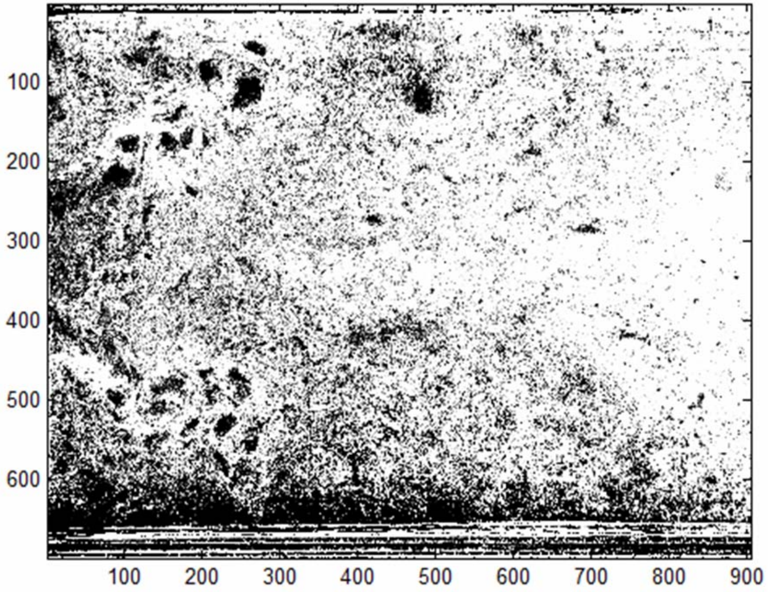
Yields excellent flashback safety up to 620 K and stoichiometric conditions

$\dot{m} = 130\,\mathrm{kg/h},\ T_{in} = 620\,\mathrm{K}$



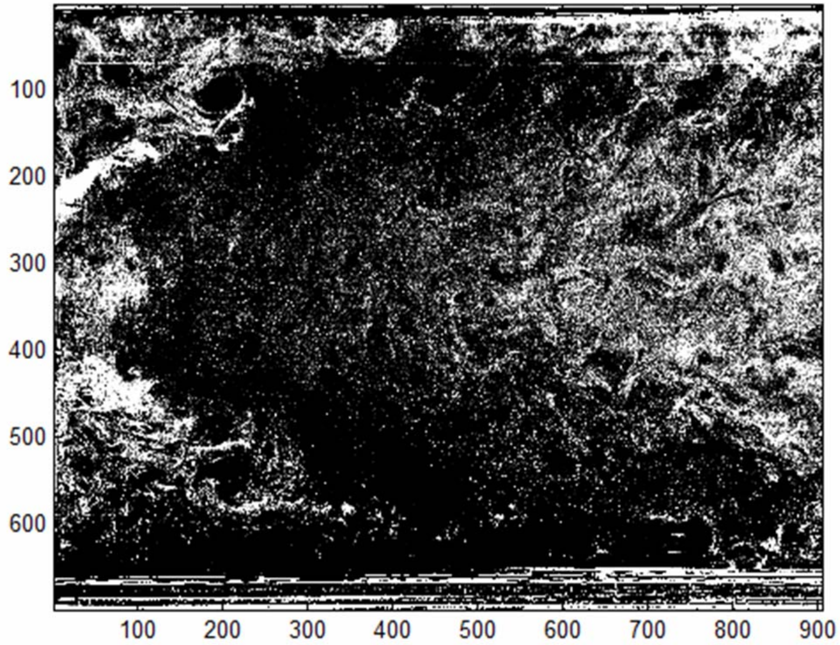
Courtesy: Thoralf Reichel (thoralf.reichel@tu-berlin.de)

Gas Fired Tests – Flame Localisation



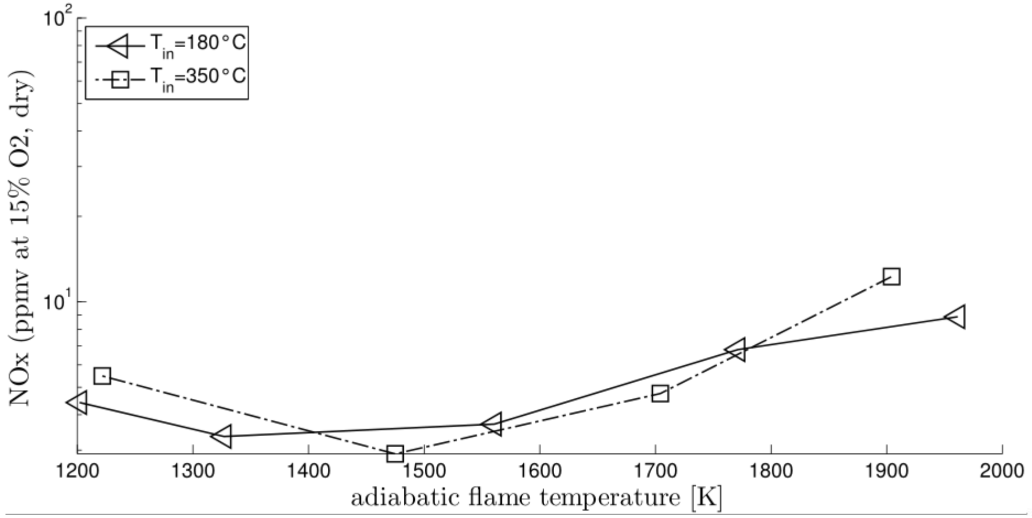
← Isothermalcase: $\phi = 0$

Reactingcase: $\phi > 0$ →



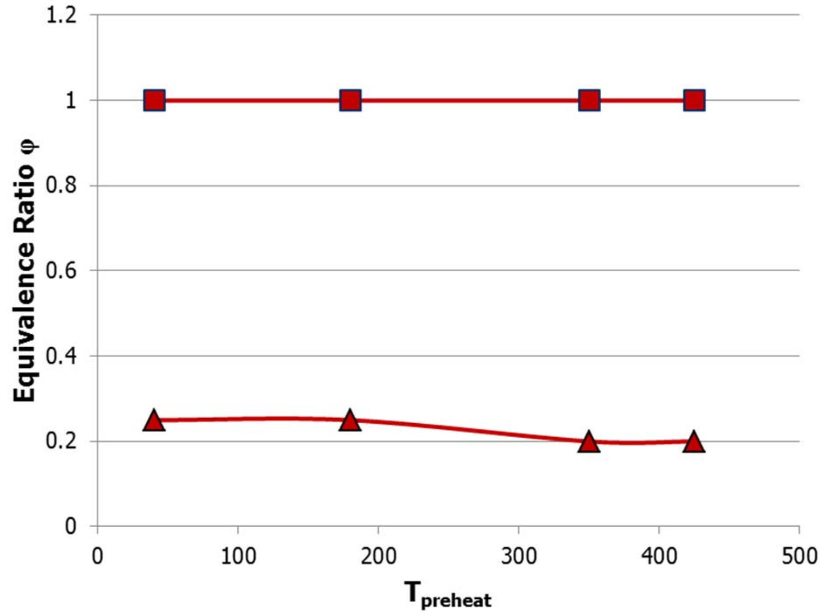
Courtesy: Thoralf Reichel (thoralf.reichel@tu-berlin.de)

Emission Characteristics of H_2 combustor



Low NOx

Flash back Free operation



Reichel, T. G., Terhaar, S., Paschereit, O. C., 2015, “Increasing Flashback Resistance in Lean Premixed Swirl-Stabilized Hydrogen Combustion by Axial Air Injection”, J. Eng. Gas Turbines Power 137(7)

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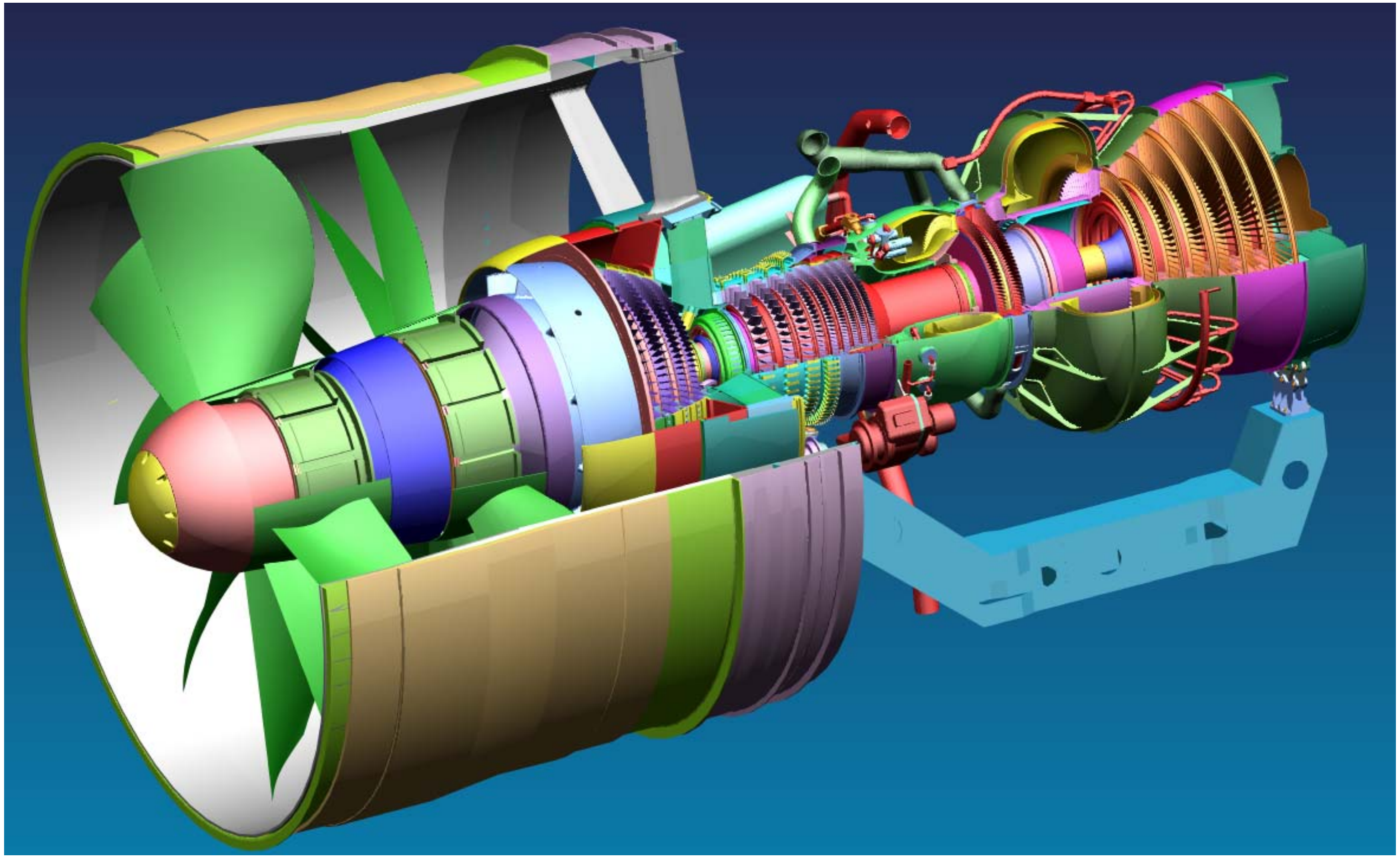
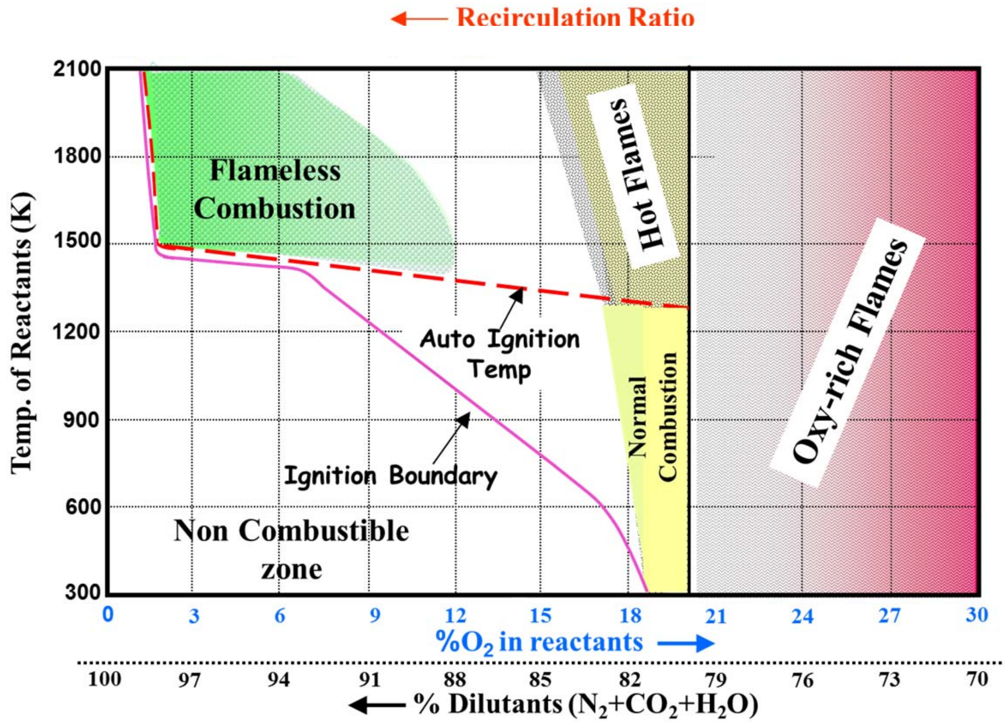
The AHEAD hybrid engine



Flameless Combustion

- Recirculation of combustion products at high temperature (> 1000°C)
- Reduced O_2 concentration in the reactants
- Transparent flame with low acoustic oscillation
- Distributed combustion zone
- Reduced temperature peaks
- Damköhler number around unity
- Low NO_x emission



Rao, G.A., and Levy, Y.,“ A New Combustion Methodology for Low Emission Gas Turbine Engines”, 8th HiTACG conference, July 5-8 2010, Poznan

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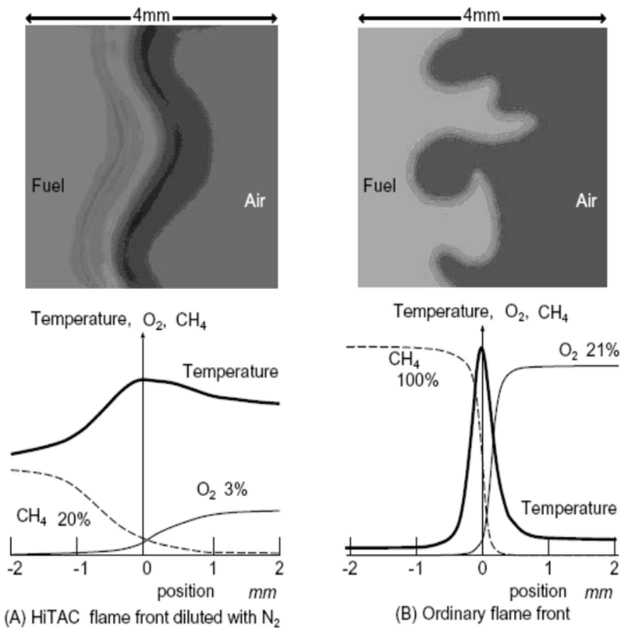
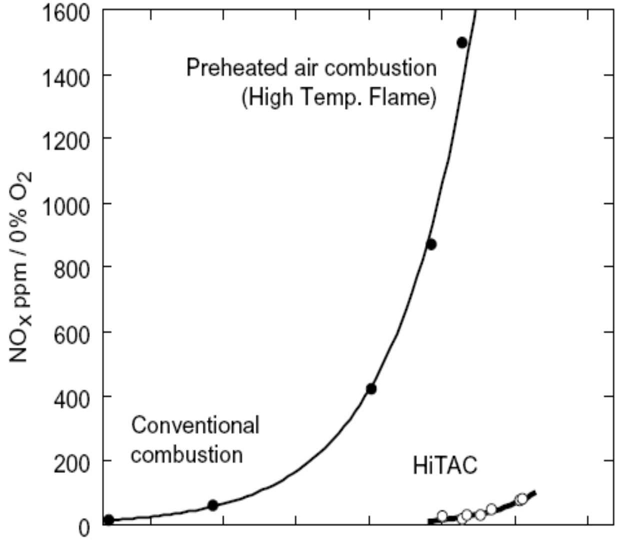
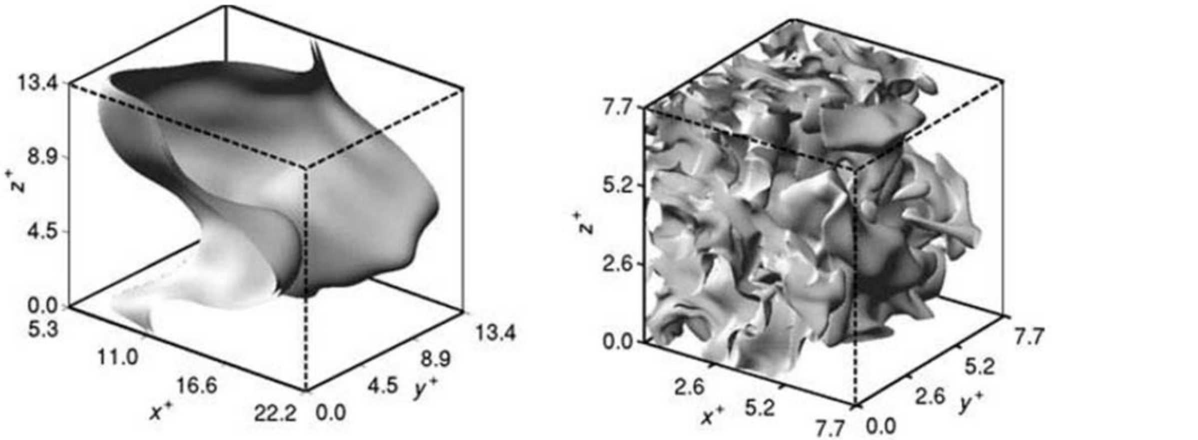
Flameless Combustion





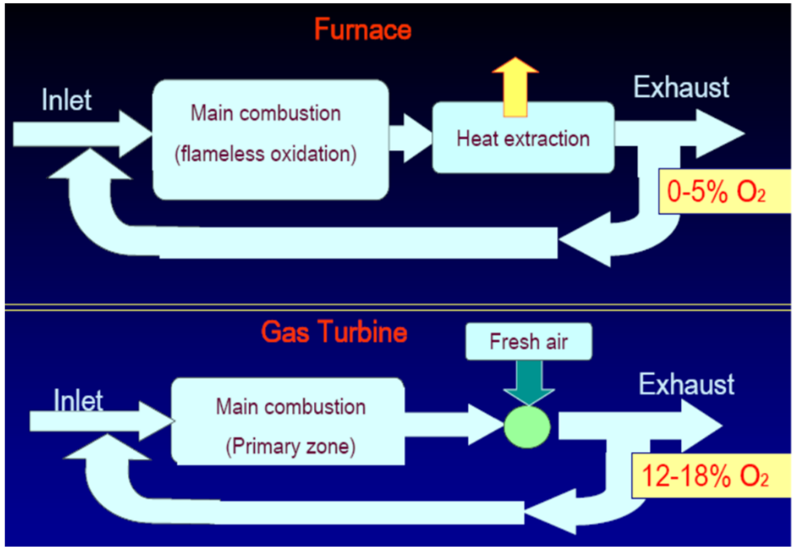
High Temperature Air Combustion : From Energy Conservation to Pollution Reduction, Tsuji, Hiroshi etal, CRC Press, 2003

Minamoto Y, et al. Reaction zones and their structure in MILD combustion. CST 2014;186:1075-1096



Comparison of reaction rate iso-surfaces between DNS of a classical premixed flame (left) and a case within the FC regime (right). [109].

Problems for FC in GT

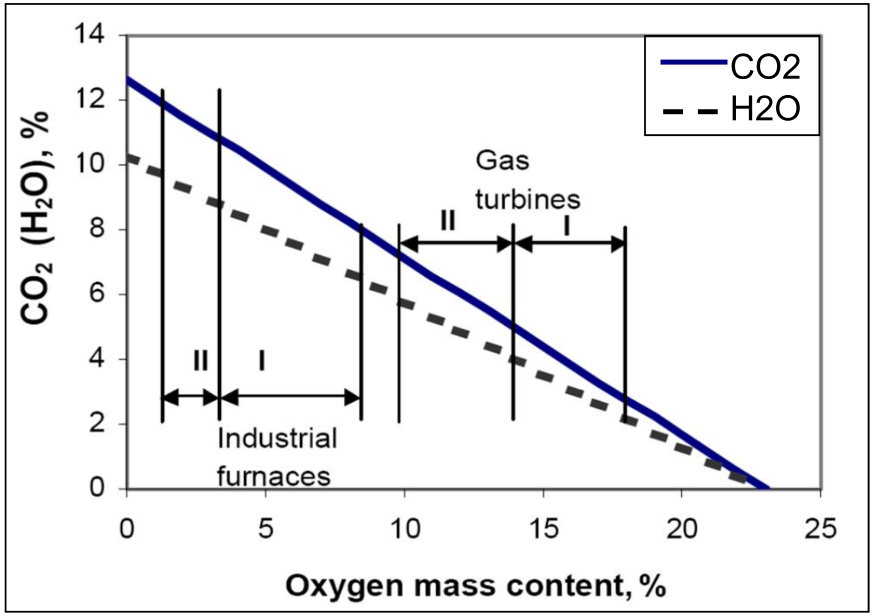


Schematic Representation of the difference between Industrial furnace and Gas turbine Combustor
(Levy. Y., Floxcom Report , 2005)

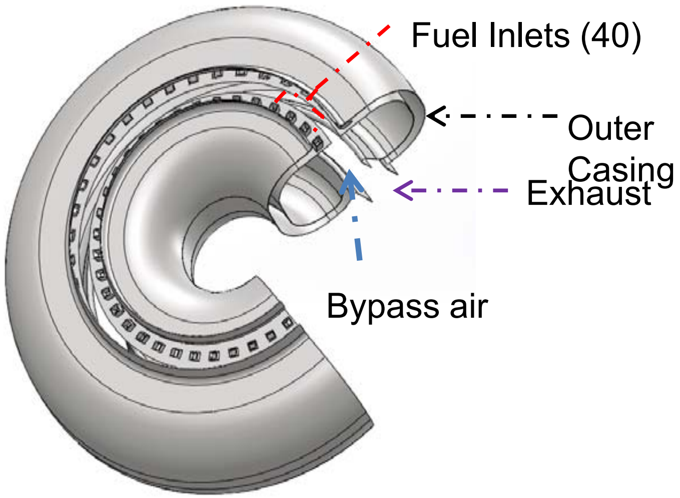
Main Challenges for FC in Gas Turbines

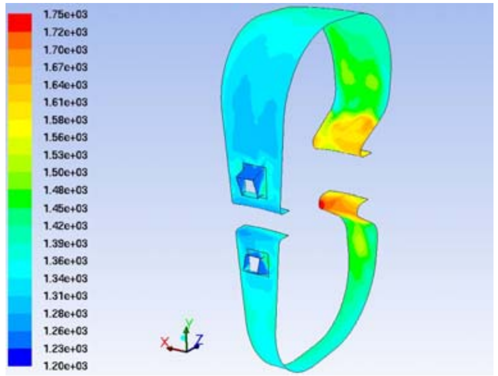
- The O2 concentration in the exhaust of a GT combustor is relatively very high
- The operational range of FC combustors is narrow
- The volume required by the FC combustor is large, an important constraint for aircraft applications

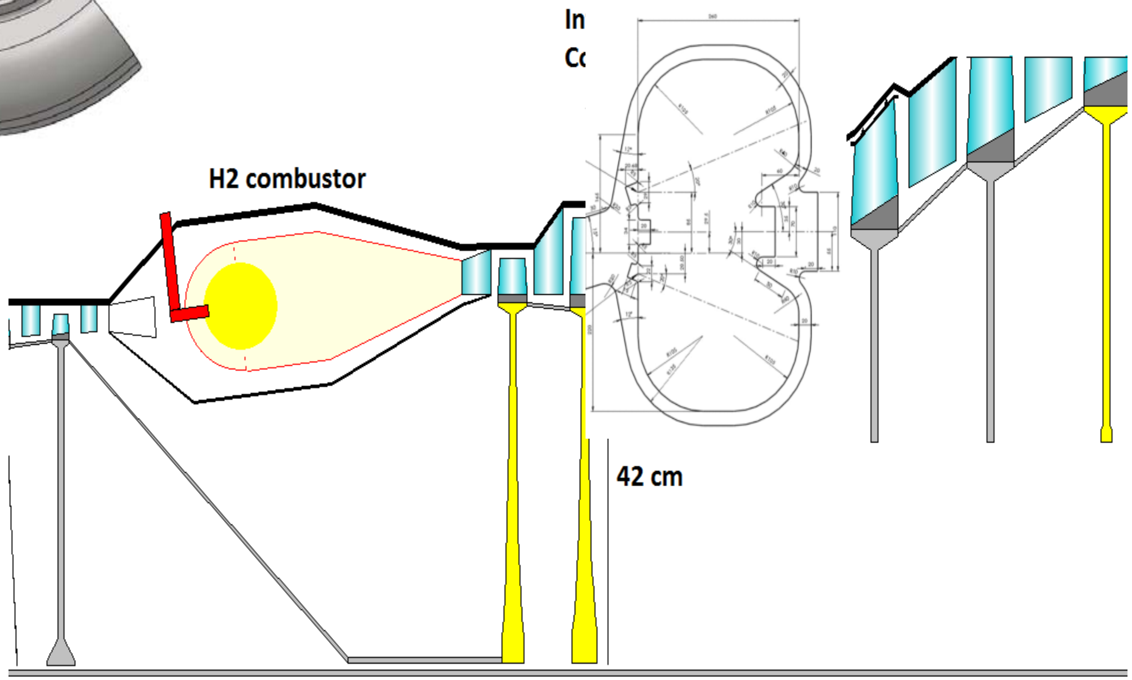
O2 Concentration in Industrial Furnace & Gas Turbine Engines
{I-before combustion, II-after combustion}
(Levy. Y. and Rao G.A, 2005)



The Inter Turbine Combustor

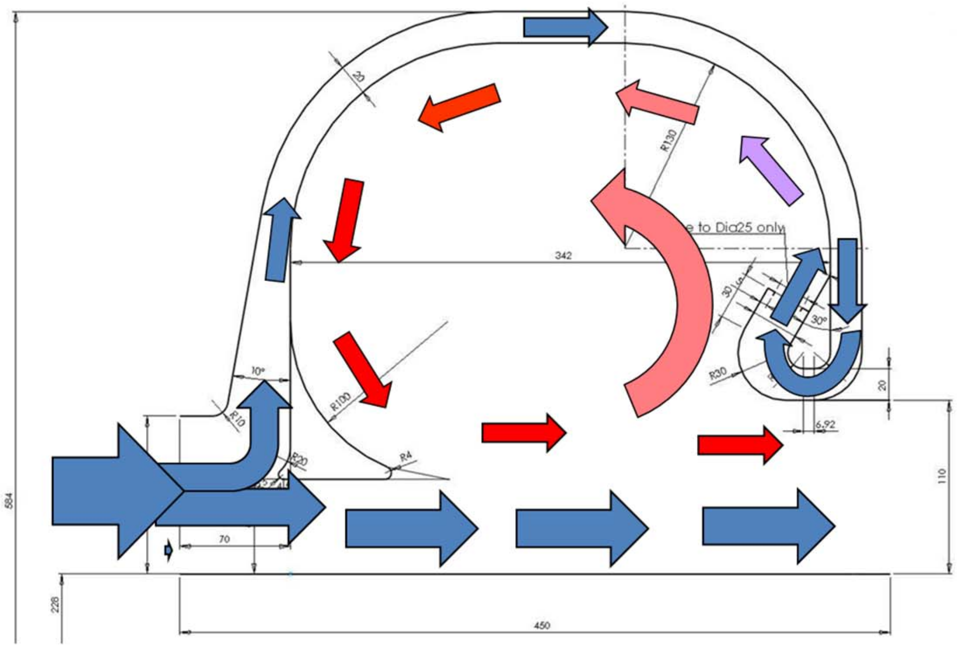




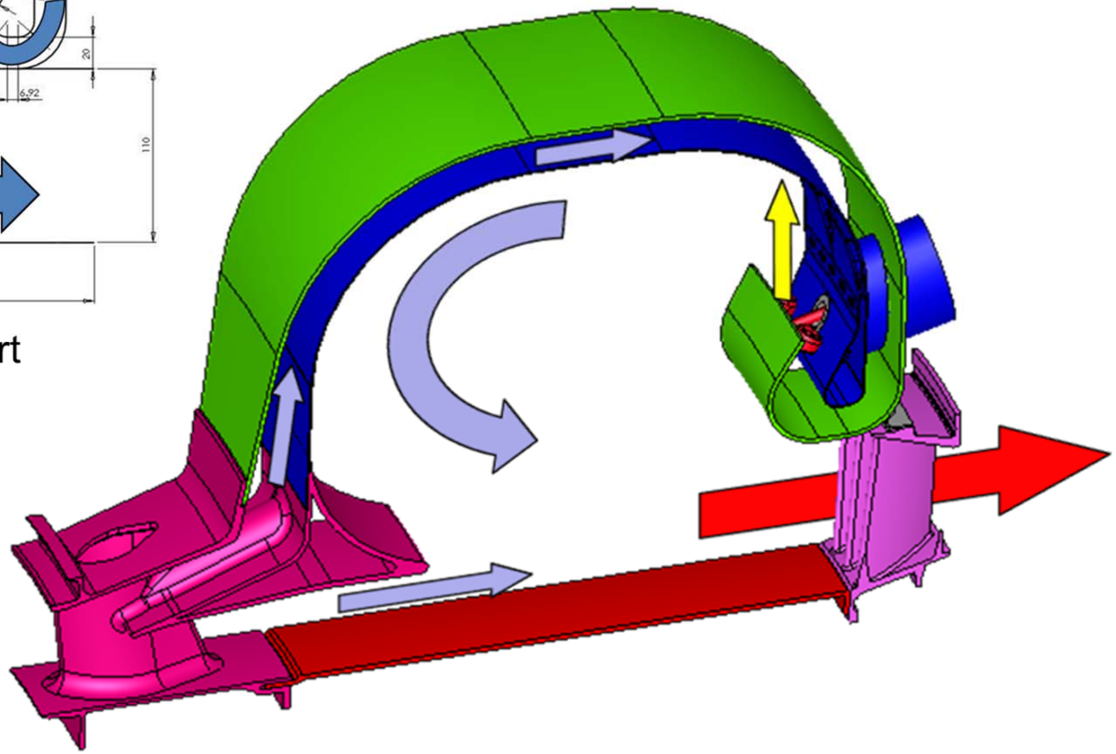


Source: Y. Levy, Technion

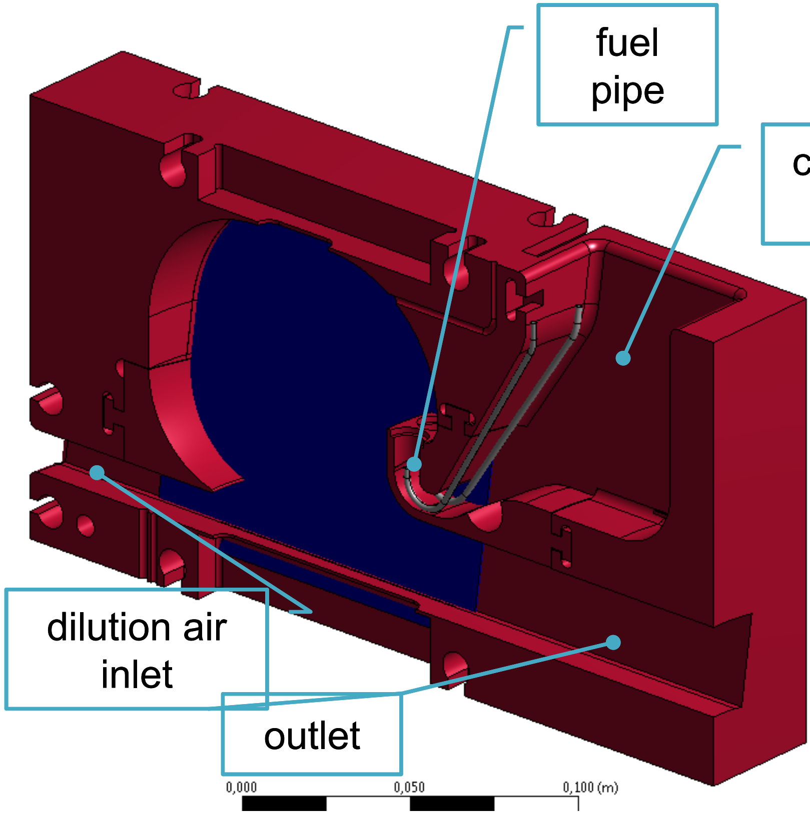
The Inter-Turbine Burner

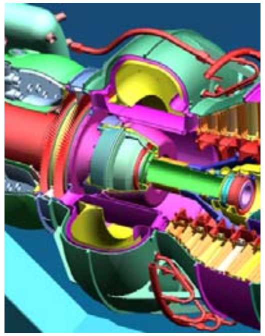


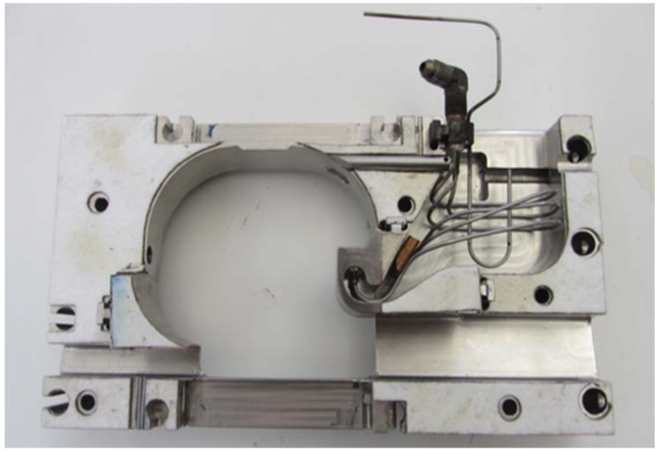
Air Inlets scheme, internal part



The atmospheric scaled combustor







Levy, Y.; Erenburg, V.; Sherbaum, V.; Gaissinski, I. *Flameless oxidation combustor development for a sequential combustion hybrid turbofan engine.* Proceedings of ASME Turbo Expo, 2016

Y. Levy, Technion

Late Prof. M. Costa
IST Portugal

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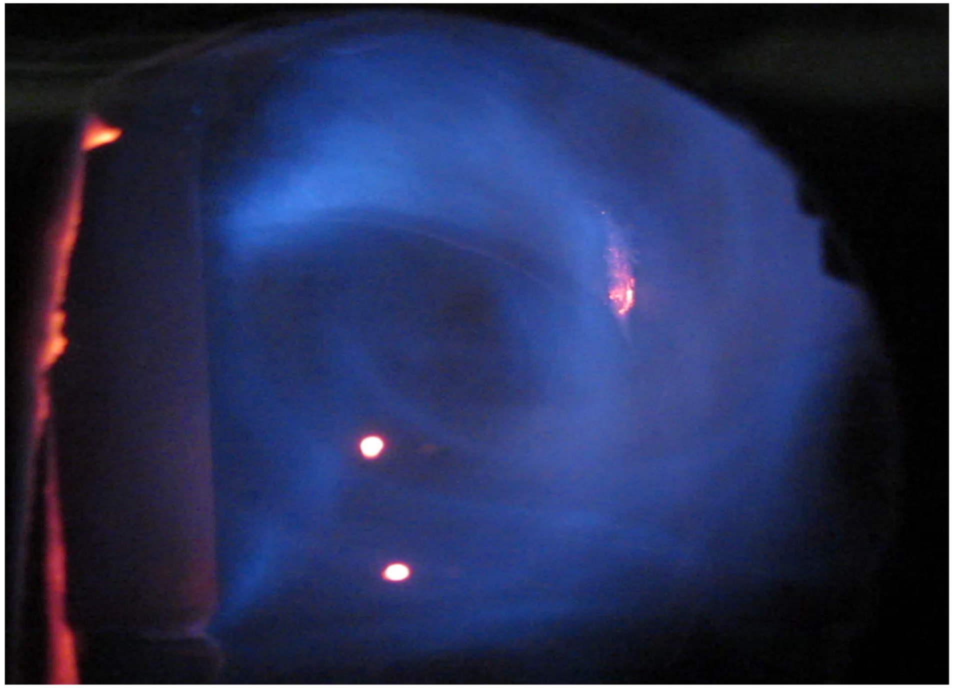
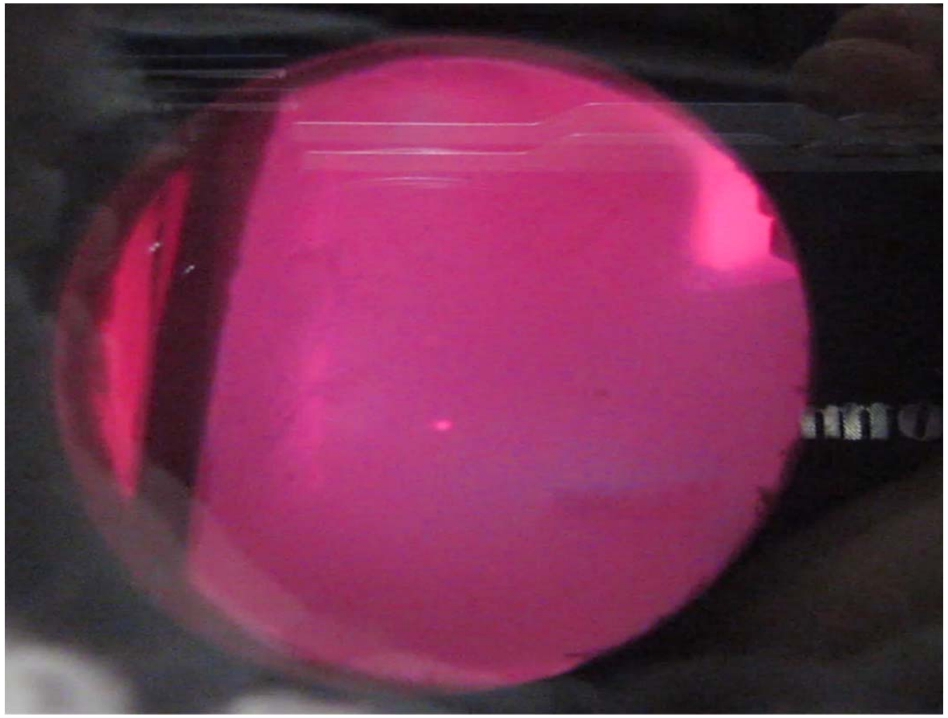
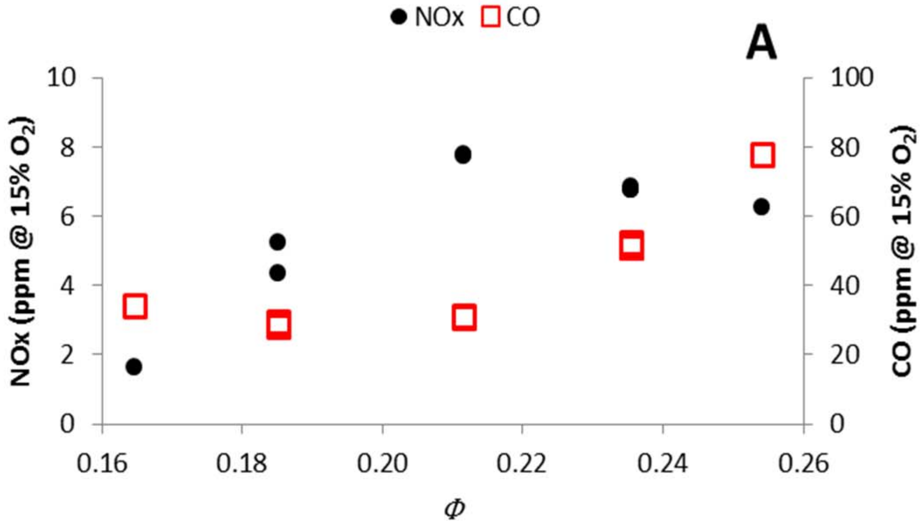
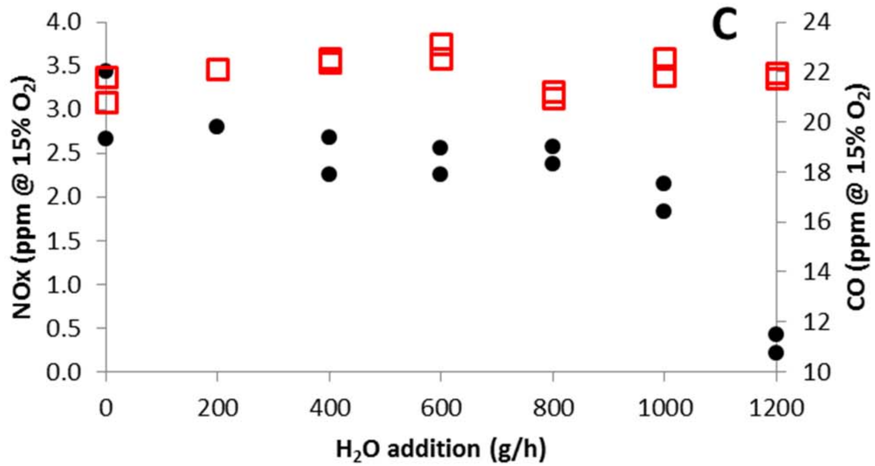
Towards Flameless Combustion

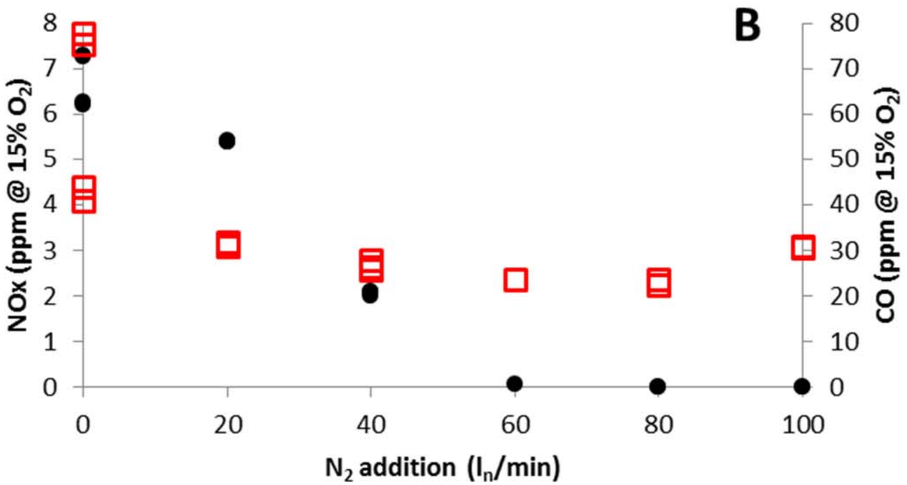




Results from the experiment







Levy, Y.; Erenburg, V.; Sherbaum, V.; Gaissinski, I.
Flameless oxidation combustor development for a sequential combustion hybrid turbofan engine.
Proceedings of ASME Turbo Expo, 2016

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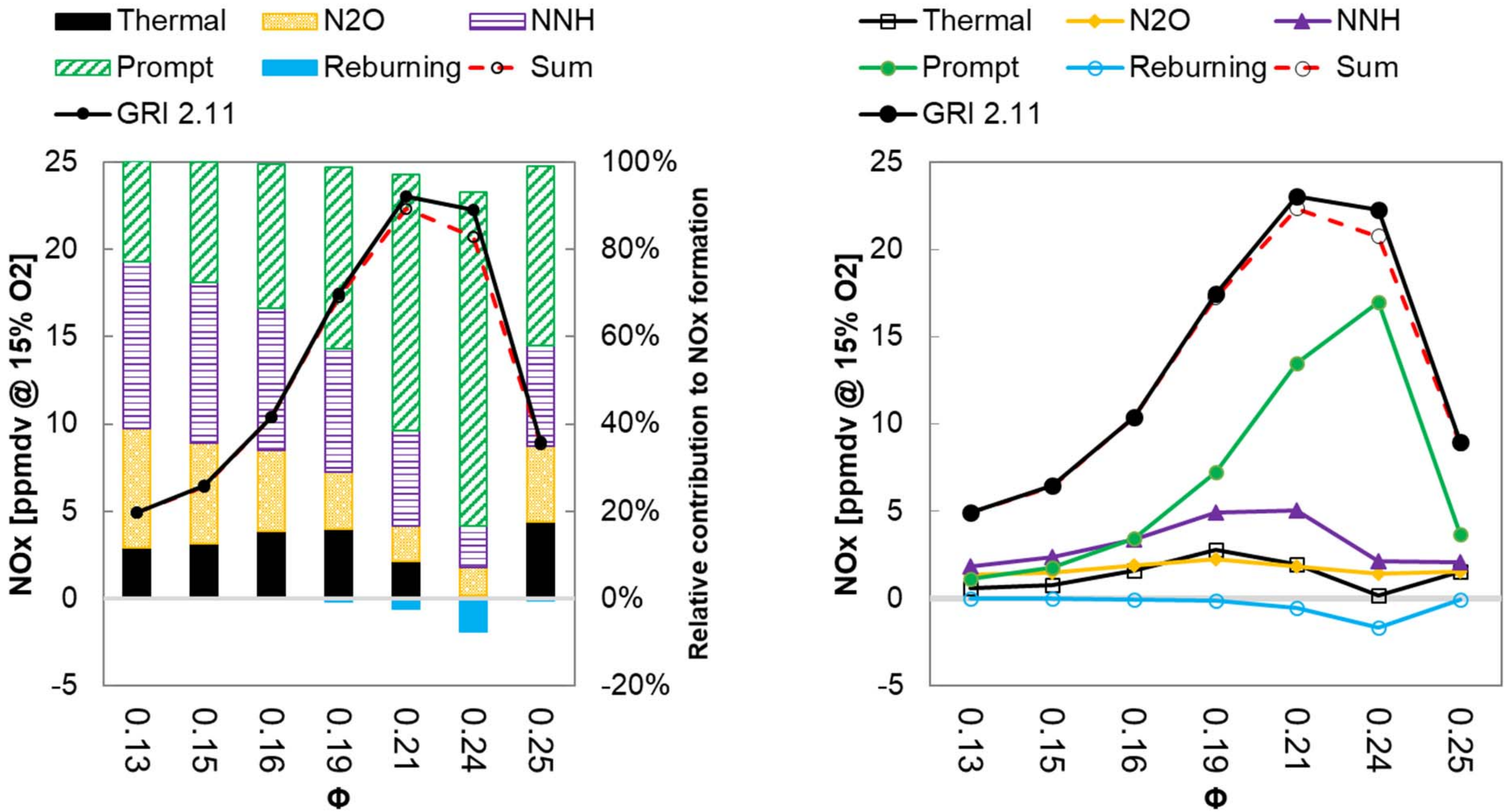
NO_x formation analysis



A.A.V. Perpignan, A. Gangoli Rao, "Effects of chemical reaction mechanism and NOx formation pathways on an inter-turbine burner", *The Aeronautical Journal* 123 (1270), 1898-1918, 2019.

Advantages of the hybrid engine

- Breaks the paradox between CO_2 and NOx
- Enables substantially lower emissions during idling
- Reduction in turbine inlet temperature
- Better off design performance of the engine
- Reburning of NOx in the second combustion chamber

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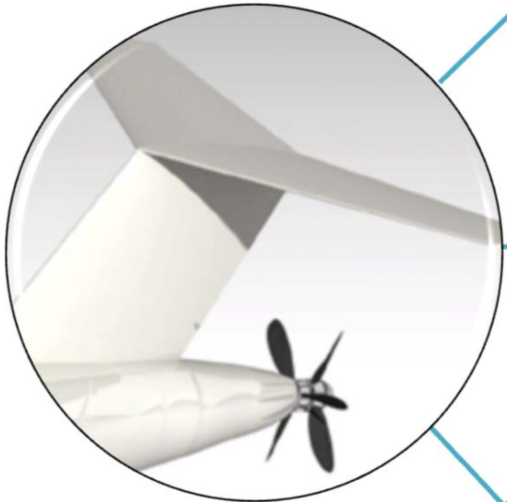
The APPU project

TU Delft SAFRAN AIRBUS Rotterdam The Hague Airport

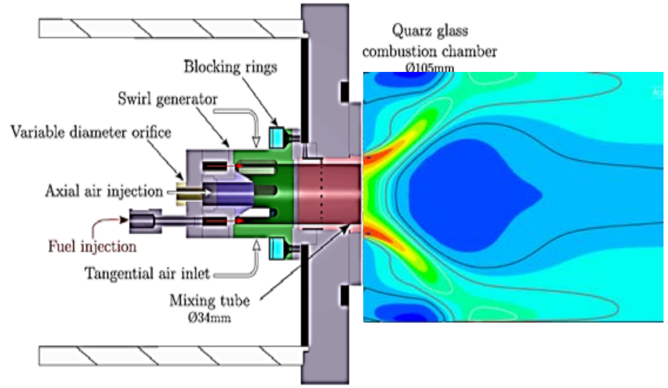
TU Delft

Advantages



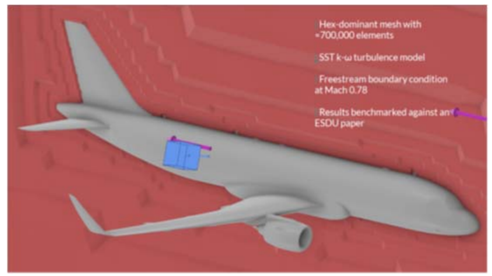
H_2 Fuel

- CO_2 free auxiliary thrust
- CO_2 free auxiliary power
- Green taxiing
- Enables Energy Mix



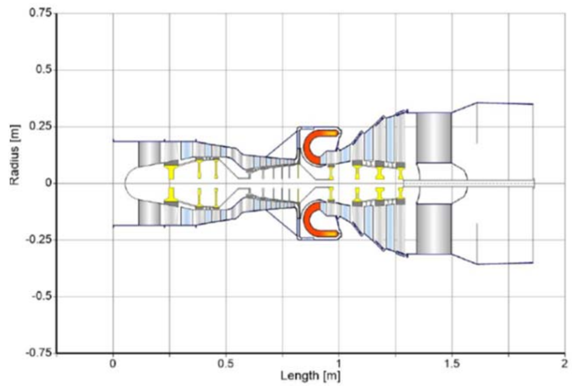
Aft Propulsor

- High propulsive η due to BLI
- Improved aircraft drag characteristics
- Improved ground operations
- Less severe "engine out" condition



System integration

- Minimal design changes
- CO_2 reduction ~ 25%
- Improved handling qualities
- Improved reliability
- Fuel production @ airport



The APPU project team

Dr. Arvind Gangoli Rao
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Project Leader

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Assistant Professor
WP1 Leader

Prof.dr.ing. Georg Eitelberg
Full Professor
WP2 Leader

Prof.dr.ir. Leo Veldhuis
Full Professor & Section Head
FPP
WP3 Leader

Martijn van Sluis, MSc
PhD Candidate

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WP1 Co-Lead

Dr. Ivan Langella
Assistant Professor
WP2 Co-Lead

Dr.ir. Tomas Sinnige
Assistant Professor
WP3 Co-Lead

Kaushal A. Dave, MSc
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Dr. Feijia Yin
Assistant Professor

Dr.ir. Ferry Schrijer
Assistant Professor

Ir. Gioele Ferrante

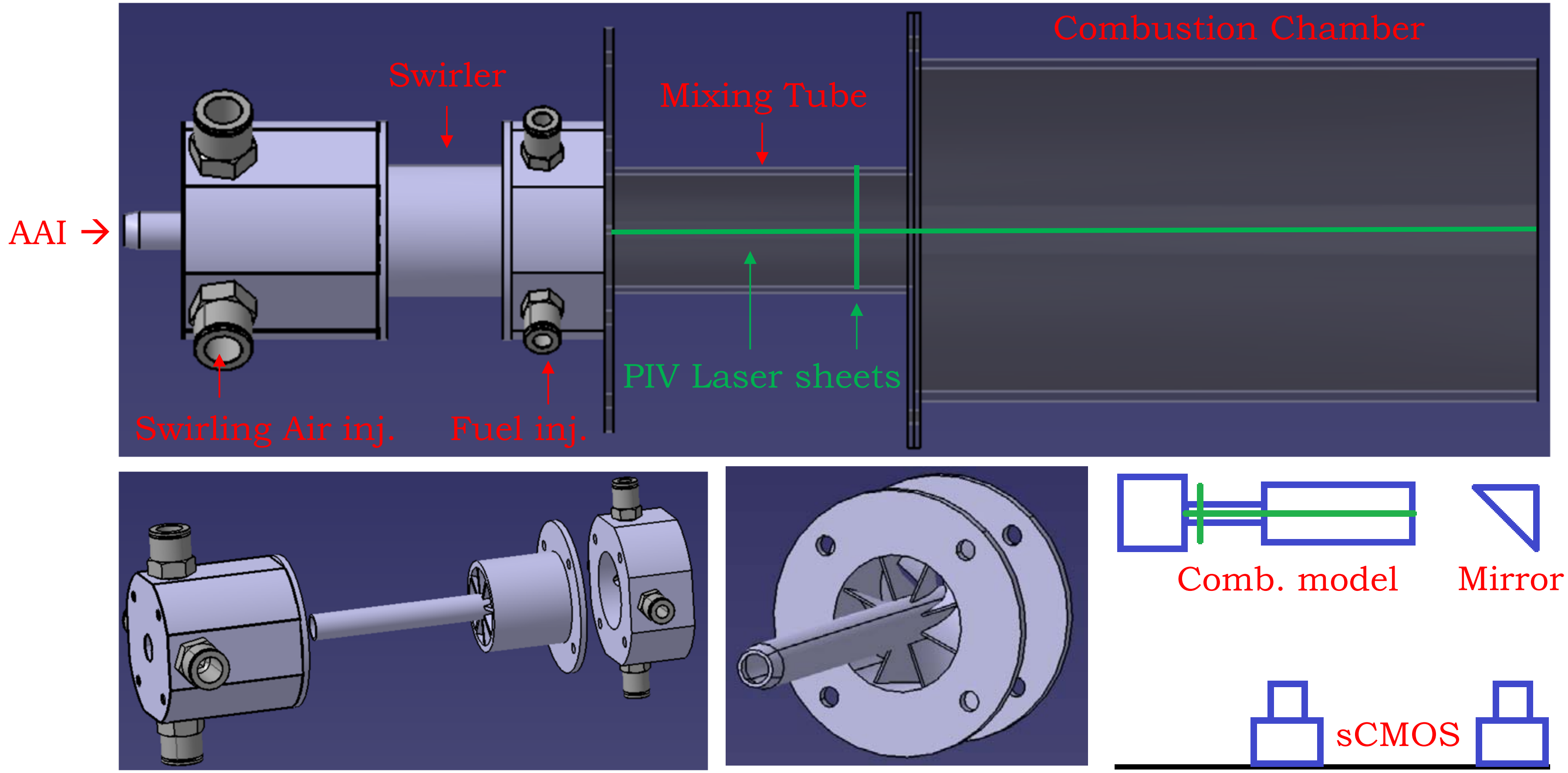
SAFRAN

AIRBUS

Rotterdam The Hague Airport

TU Delft

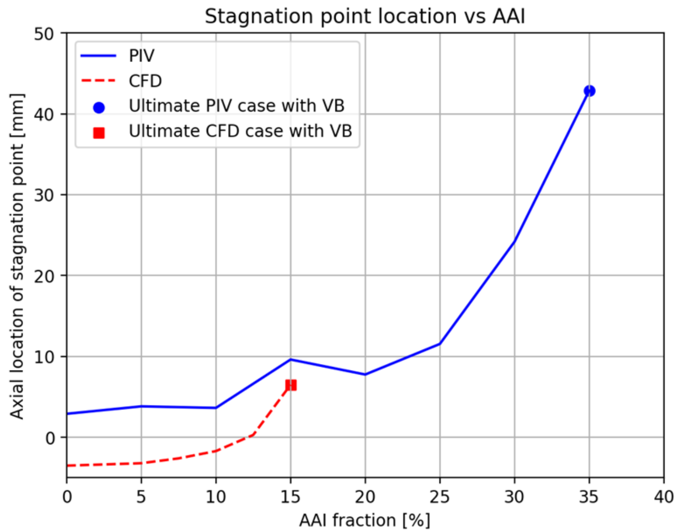
Experimental Model: Axial Vane Swirler



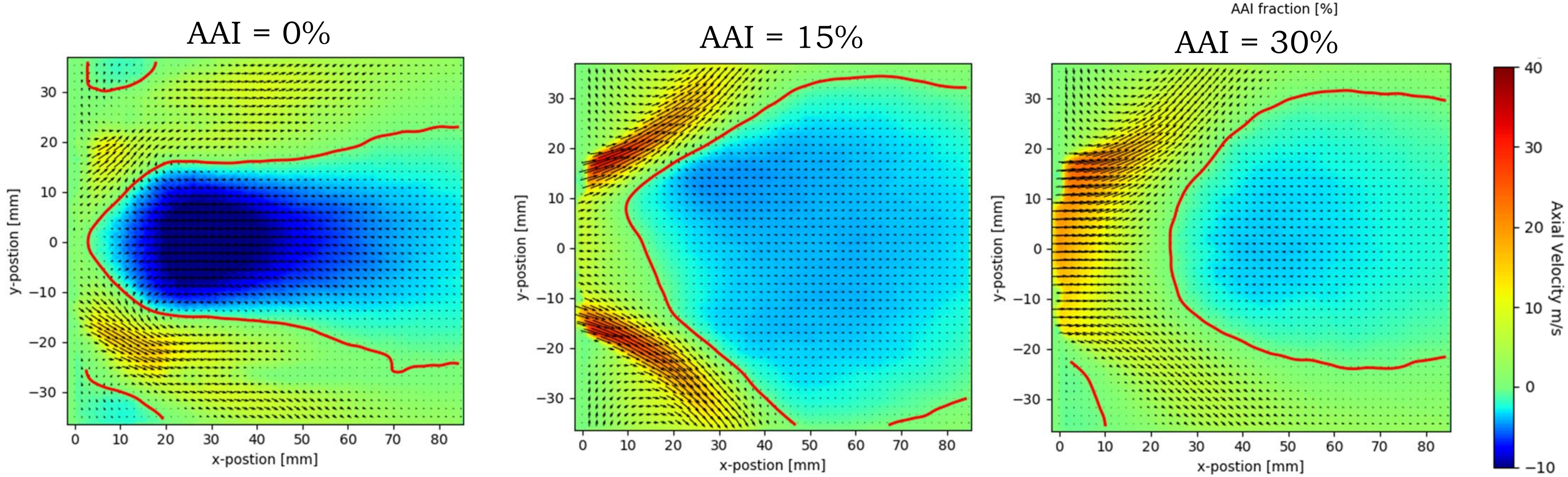
Courtesy: Simon Vermijlen

PIV Results: Axial Swirler Centerline

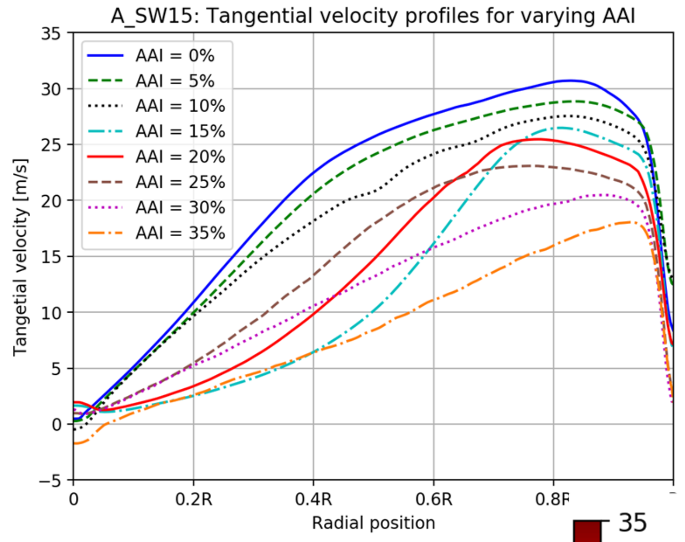
- Increasing AAI pushes stagnation point downstream
- CFD underestimates axial position of stagnation point
- CFD overestimates destabilizing effect of AAI



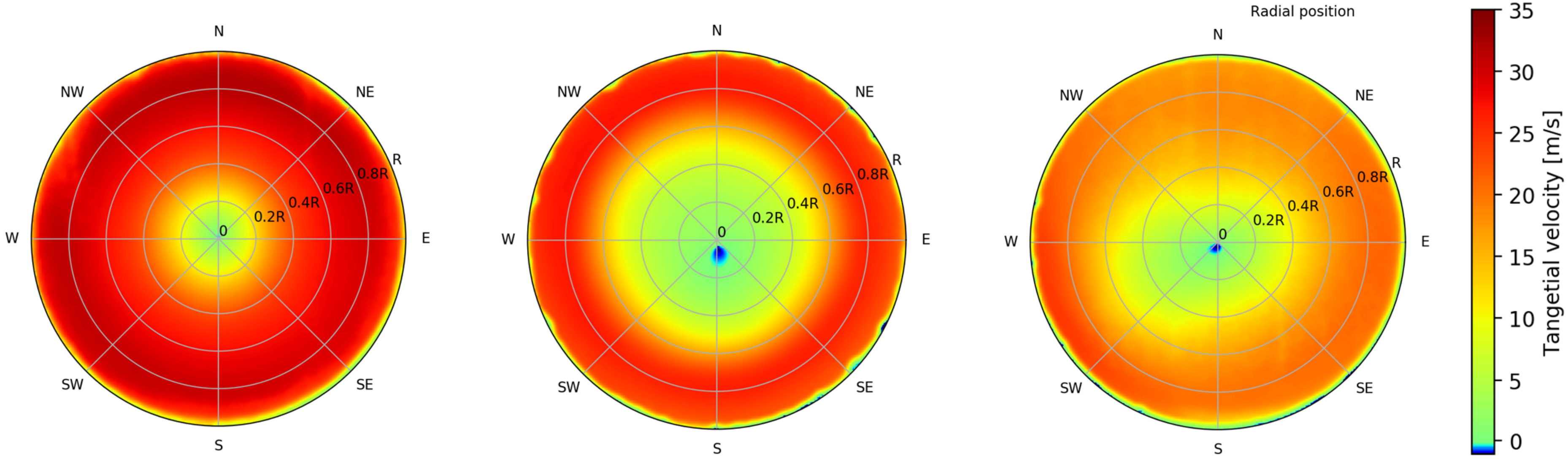
Courtesy: Simon Vermijlen



PIV Results: Axial Swirler Cross section



- Increasing AAI decreases rotation (swirl)
- Conversion to Swirl number pending
- CFD underestimates rotation (swirl)



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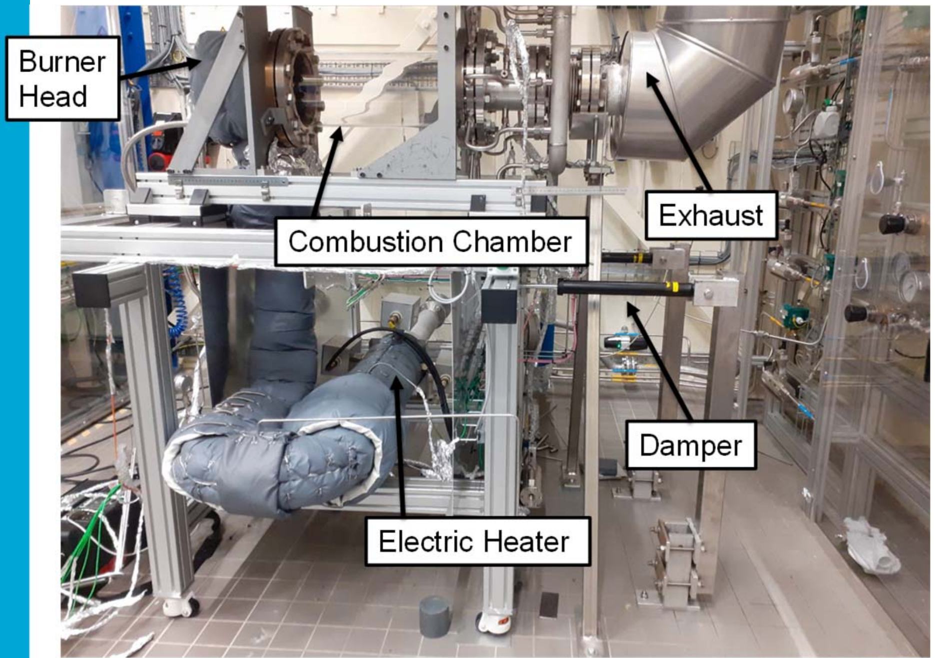
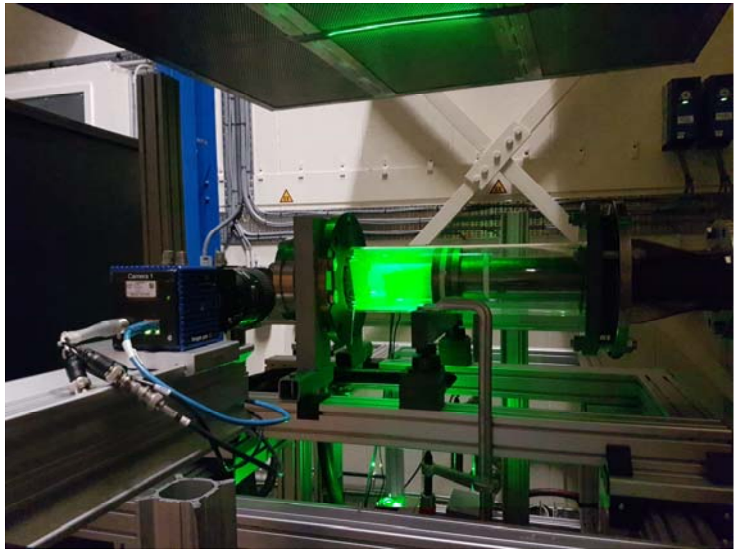
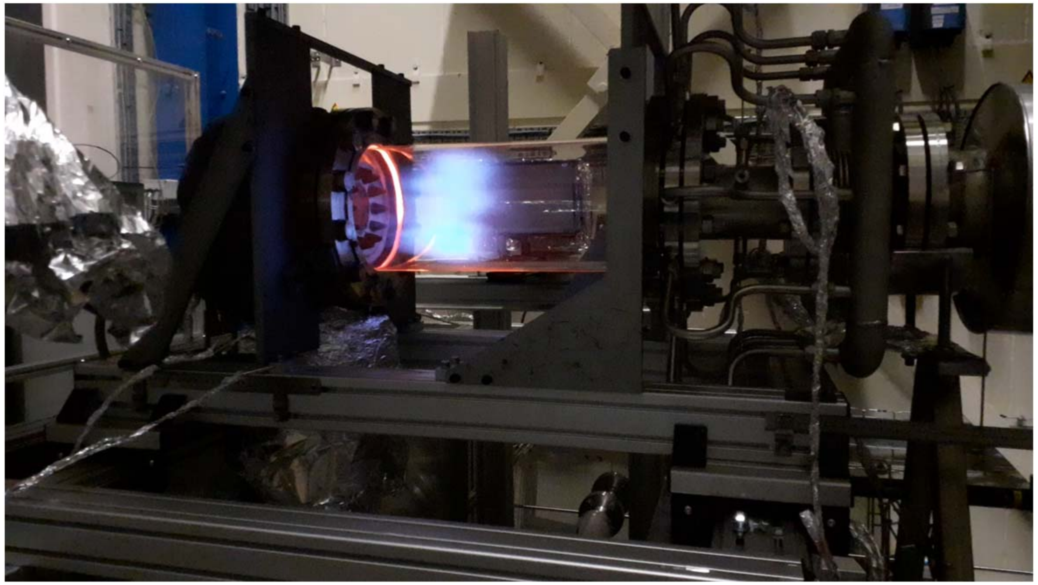
Courtesy: Simon Vermijlen

Clean Combustion Lab







- M. P. Huijts, A. A. V. Perpignan, A. Gangoli Rao, “An experimental and Numerical Investigation of the aerodynamic characteristics of a flameless combustor”, GT2019-90895, ASME TurboExpo 2019, Arizona
- Rishikesh Sampat,Ferry F.J. Schrijer and A. Gangoli Rao, “ Turbulent Interaction of Jet with Co-Flow”, 55thInternational Conference on Applied Aerodynamics, March 2020, France

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Points of attention

- Physics is independent of opinions!
- Aviation will grow substantially in the next few decades.
- Therefore the emissions from aviation will become significant.
- "No fuel is cheap when you have to make it your self".
- "Energy Mix" will be the key for future of aviation.
- Life cycle analysis should be looked into carefully before jumping on to a solution.
- The choice of energy source/carrier will be customised to aircraft mission.
- Hybrid combustion will enable energy transition in aviation
- Technology cannot be the only solution to mitigate the ill effects of Human Greed!

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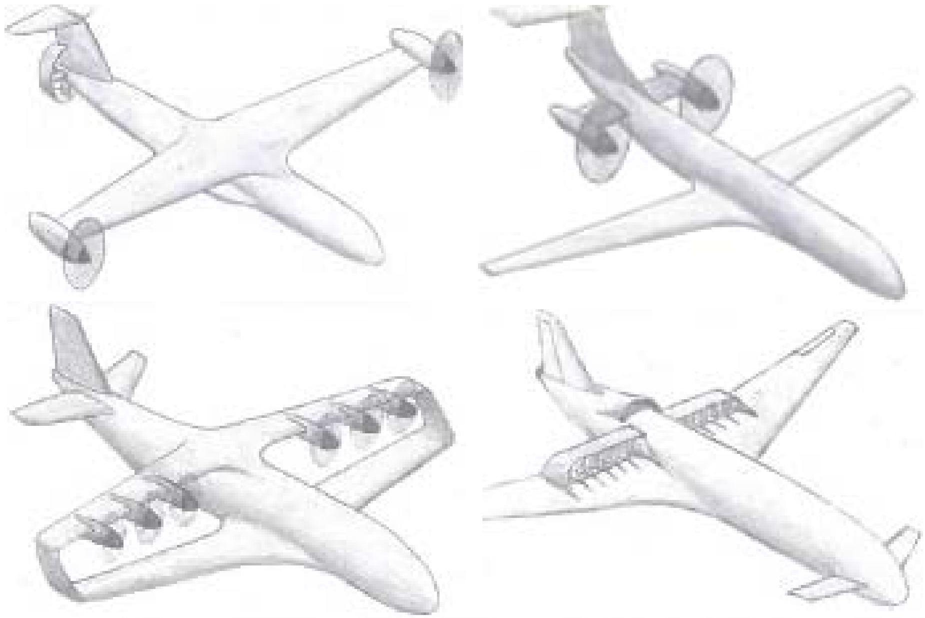
Thank You

Prediction is difficult, especially if it is about the future: Niels Bohr



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