June 20, 2023

Technology Collaboration Programme on
Advanced Motor Fuels

The development of ammonia and methanol burning marine engines

German Weisser
Winterthur Gas & Diesel Ltd

WIN GD

Presentation outline

Setting the stage

AMF Task 60 (formerly Annex 60)

Purpose: Assessment of fuel options that have emerged or significantly developed since the 2014 report (AMF Annex 41).

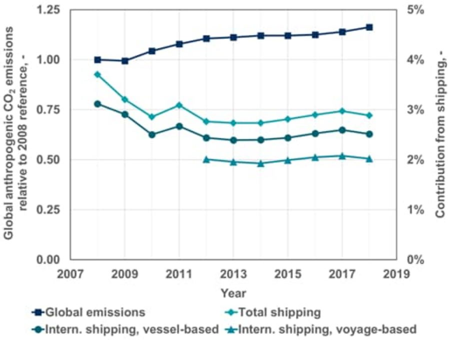
Table 13. Summary of Evaluation of Propellant Systems

	IFO	LSFO	MGO/GTL/ BTL	HVO/SVO/ FAME	MeOH	DME/LPG	LNG/LBG
Engine and fuel system cost	Drop in	Drop in	Drop in	Drop in	Dual fuel	Gas tank	Dual fuel Cryo tanks
Projected fuel cost		Refining	Refining	Land use		Infra structure	Infra structure
Emission abatement cost	SOx, NOx, PM, CO_2	NOx, PM, CO_2					
Safety related cost					Flash point	Ventilation	Press/temp
Indirect cost				Ethics	Cargo space	Cargo space	Cargo space

Serious impediment

Significant cost

Feasible solution available



Low-speed engine DF technology state of the art

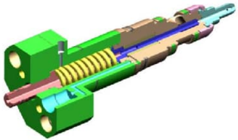
Variants of dual-fuel engine concepts applied on two-stroke engines

The MAN ME-GI concept:

- Diesel-type combustion of a gas jet
- Injection pressure in the range of 150 to 315 bar, depending on engine load
- Ignition by means of pilot fuel via backup fuel system

Fuel varieties covered by the concept and derivatives:

- LNG, bio-methane, synthetic meth
- Ethane (ME-GIE)
- LPG (ME-LGIP)
- Methanol (ME-LGIM)
- VOC (LNG/VOC blends ME-GIE)



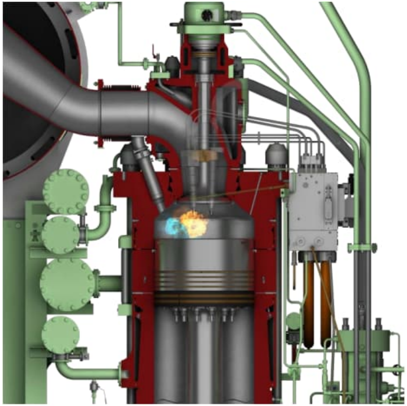


Illustration of ME-GI working principle (right) and gas injector (left) as key system feature, from L. Ryberg Juliussen et al, 2013, The MAN ME-GI engine: From initial system considerations to implementation and performance optimisation, CIMAC

Low-speed engine DF technology state of the art

Variants of dual-fuel engine concepts applied on two-stroke engines

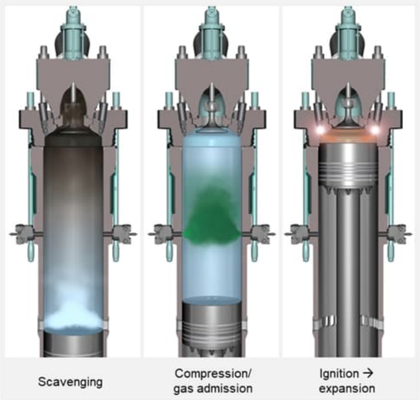


Illustration of WinGD X-DF working principle, from I. Nylund I., M. Ott, 2013, Development of a dual fuel technology for slow-speed engines, CIMAC

The WinGD X-DF concept:

- Engine operating according to the Otto process
- Pre-mixed ‘Lean burn’ technology
- Low pressure gas admission at ’mid stroke’
- Ignition by pilot fuel in prechamber
- Combustion in main chamber initiated and enhanced by hot jets

Largely similar approach used on MAN ME-GA engines

Fuel varieties covered by the concept:

- LNG, bio-methane, synthetic methane
- VOC (LNG/VOC blends)

Development plans of low-speed engine developers

Fuel applicability map - MAN ES

Fuel types	MC	ME-B	ME-C	ME-GI	ME-GA	ME-GIE	ME-LGIM	ME-LGIP
0-0.50% S VLSFO	Design	Design	Design	Design	Design	Design	Design	Design
HFO	Design	Design	Design	Design	Design	Design	Design	Design
Biofuels	Design	Design	Design	Design	Design	Design	Design	Design
LNG	-	-	Retrofit	Design	Design	Retrofit	Retrofit	Retrofit
LEG (Ethane)	-	-	Retrofit	Retrofit	-	Design	Retrofit	Retrofit
Methanol / Ethanol	-	-	Retrofit	Retrofit	-	Retrofit	Design	Retrofit
LPG	-	-	Retrofit	Retrofit	-	Retrofit	Retrofit	Design
Ammonia	-	-	Retrofit	Retrofit	-	Retrofit	Retrofit	Retrofit

Overview of fuel types and their applicability / retrofit ability on different engine design variants, from R. Bidstrup, 2021, MAN B&W Ammonia fueled engine development status, 42. Informationstagung zur Schiffsbetriebsforschung

Development plans of low-speed engine developers

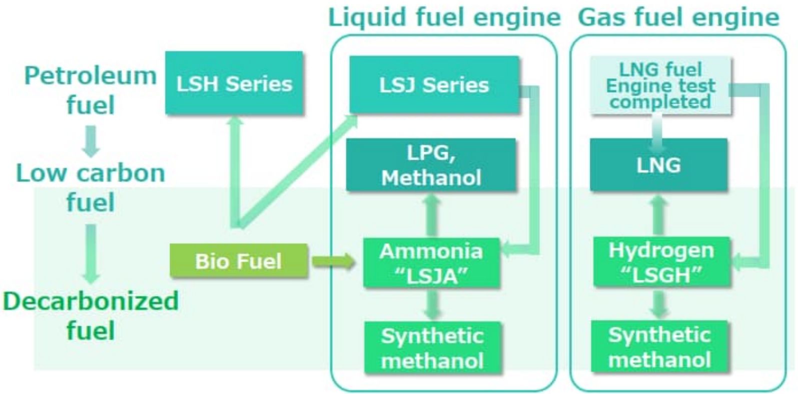
Fuel applicability map - WinGD

Fuel Type	Drop-in capable	X-engines	X-DF engines
0 – 0.5%S VLSFO	n/a	Available	Available
HFO	n/a	Available	Available
Bio-diesel	✓	Available	Available
LNG	n/a	Retrofit	Available
Bio-methane	✓	Retrofit	Available
Synthetic methane	✓	Retrofit	Available
Ammonia	Dual- / Tri-Fuel	In Development	In Development
Methanol/ Ethanol	Dual- / Tri-Fuel	In Development	In Development
Lignin- derived biofuel	(✓)	Available	Available

Overview of fuel types and their applicability / retrofit ability on different engine design variants, from D. Schneiter, S. Goranov, P. Krähenbühl, D. Schäpper, M. Spahni, G. Weisser, 2021, WinGD's X-act initiative: A holistic approach towards sustainable shipping, 18th Symposium „Sustainable Mobility, Transport and Power Generation“

Development plans of low-speed engine developers

Fuel applicability map - JEng



Overview of fuel types and their application on different engine design variants, from K. IMANAKA, Y. KINOSHITA, K. EDO, The latest technological development of the J-ENG UE engine for zero emission and digital transformation, CIMAC 2023

Development plans of low-speed engine developers

Technological approach - JEng

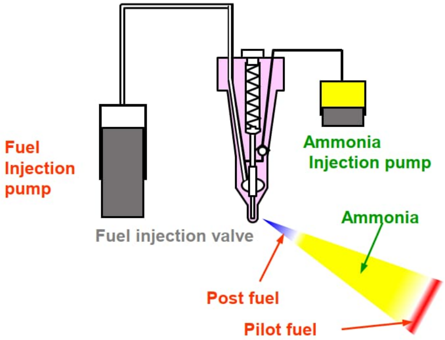


Figure 11. Outline of stratified injection system

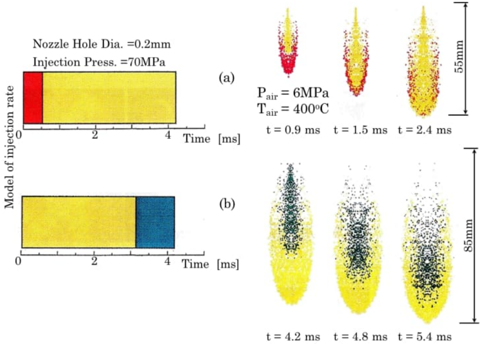


Figure 12. CFD analysis result of stratified injection

Illustrations of envisaged operating principle, from K. IMANAKA, Y. KINOSHITA, K. EDO, The latest technological development of the J-ENG UE engine for zero emission and digital transformation, CIMAC 2023

Development plans of low-speed engine developers

Schedule - MAN ES

2019 – Pre-study

- ✓ NH3 combustibility investigation.

2020 – Project kick-off

- ✓ 4T50ME-X test engine received as platform for the Ammonia engine development.
- ✓ HAZID workshop on engine concept.
- ✓ Combustion chamber 1st evaluation.

2021 – Engine concept R&D

- Engine basic concept defined based on R&D and simulations.
- Ammonia fuel supply & Auxiliary systems specified and established in RCC.

2022 – Engine combustion and emission

- 1st engine confirmation at Research Centre Copenhagen (RCC).
- Specification of emission after-treatment done.

2023 – Full scale engine test

- Full scale engine test at RCC evaluated for 1st commercial design.

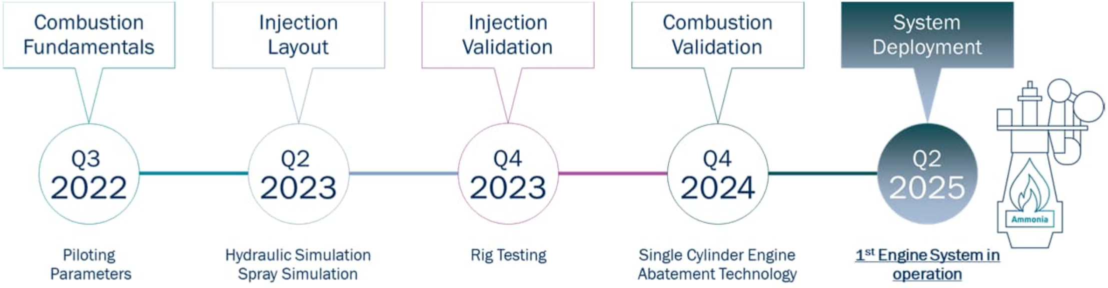
2024 – 1st engine delivery to yard

- Ammonia engine in engine programme.
- 1st ammonia fueled engine delivered to yard.

Two-stroke ammonia engine development schedule, retrieved from https://www.man-es.com/marine/strategic-expertise/future-fuels/ammonia (last accessed 20.6.2023)

Development plans of low-speed engine developers

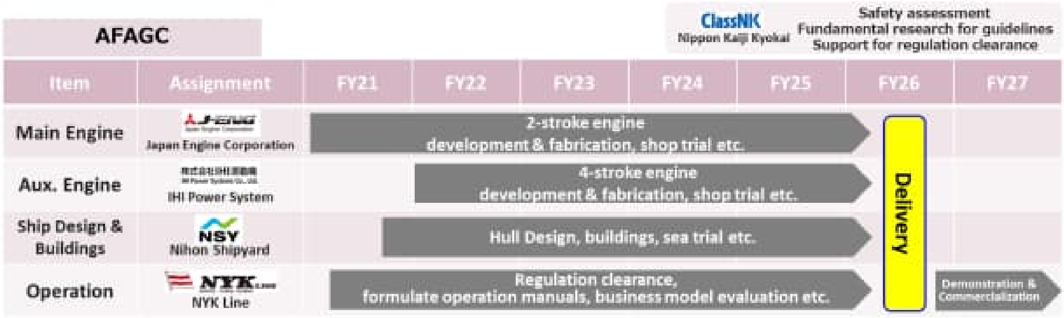
Schedule - WinGD



WIN GD

Development plans of low-speed engine developers

Schedule - JEng



JEng devlopment plans: Ammonia-fuelled ammonia gas carrier demonstration project,
Illustration from press release retrieved from https://www.j-eng.co.jp/en/news (last accessed November 18, 2021)

Development plans of low-speed engine developers

Investment into dedicated testing infrastructure - MAN ES

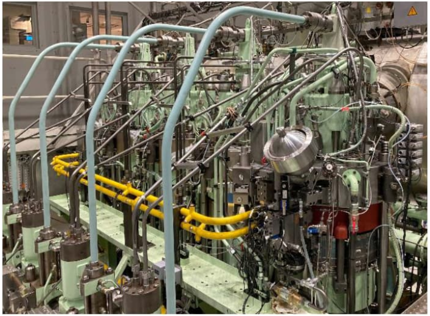


Figure 3. Photo of cylinder cover for ammonia tests mounted on the MAN B&W 4T50ME-X test engine in Copenhagen.

Photographs of new test engine, from Tradewinds (left, https://www.tradewindsnews.com/insight/first-ammonia-engines-for-commercial-use-are-due-out-in-2024/2-1-824790, retrieved 20.6.2023) and Stefan Mayer, Johan Kaltoft, Henrik Christensen, Shenghui Cong, Johan Hult, Kar Mun Pang, Julia Svensson, Johan Sjöholm, Developing the MAN B&W dual fuel ammonia engine, CIMAC 2023

Development plans of low-speed engine developers

Investment into dedicated testing infrastructure - WinGD

Development plans of low-speed engine developers

Investment into dedicated testing infrastructure - JEng

Ammonia fueled test engine

Ammonia fuel supply facility

Installed at Mitsubishi Heavy Industries, Ltd. Research and Innovation Center (Nagasaki)

JEng ammonia testing infrastructure information retrieved from https://www.j-eng.co.jp/en/solution-technology/lsja_lsgh.html (last accessed 20.6.2023)

Fundamental experimental investigations

Activities in Switzerland as example

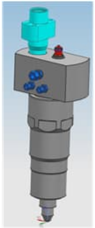
Review of earlier development at WinGD in the context of the Hercules-2 programme on the potential of methanol as a marine fuel

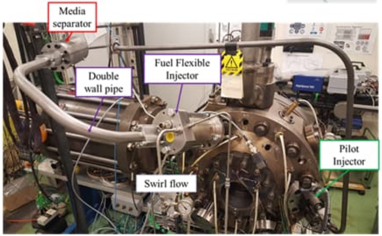
Initial investigation into combustion of ammonia at the University of Applied Sciences and Arts North Western Switzerland (featuring in various publications, e.g. K. Herrmann, S. Wüthrich, P. Süess, P. Cartier, R. de Moura, G. Weisser, Initial investigations into ammonia combustion at conditions relevant for marine engines, CIMAC 2023)

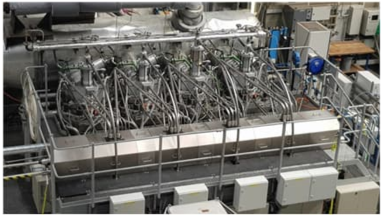
Perspective on methanol/ethanol as future fuels

Methanol / ethanol investigations in the context of Hercules-2

- Development of a fuel injection system with built-in flexibility for switching between ranging in energy content from ethanol to conventional fuels
- Test of the system on various testing platforms:
  - Injection test rig
  - Spray combuston chamber
  - RTX-6 lab engine





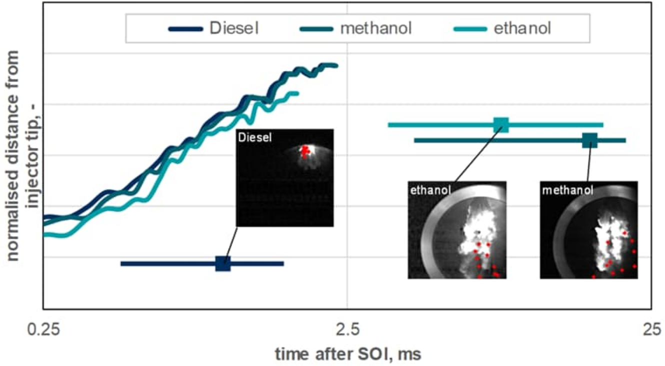


Perspective on methanol/ethanol as future fuels

Methanol / ethanol investigations in the context of Hercules - 2

Selected results (Spray combustion chamber tests):

- Spray propagation and ignition behaviour of methanol and ethanol compared to Diesel

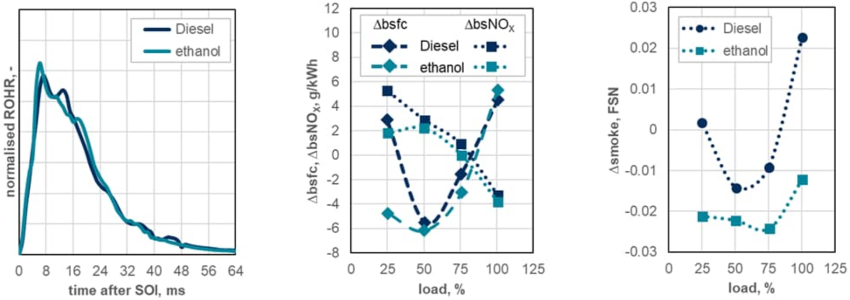


Perspective on methanol/ethanol as future fuels

Methanol / ethanol investigations in the context of Hercules - 2

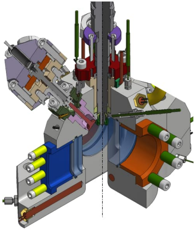
Selected results (RTX-6 lab engine tests):

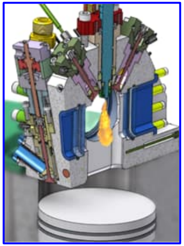
- Rate of heat release (ROHR) characteristics at full load (left) and bsfc / $bsNO_X$ impact throughout load range (middle) and smoke emissions across the load range (right) when applying ethanol in combination with adapted combustion system features



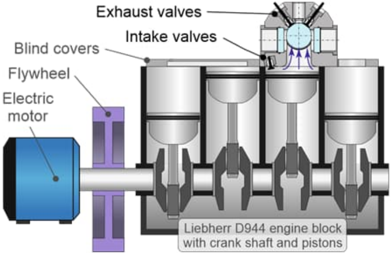
Test Facility "Flex-OeCoS"

Principle, specifications and features





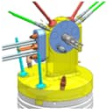
Optical combustion chamber



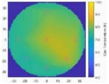
- Optical access: 4 windows optical chamber ⦸ 60×20 mm
- Engine-like compression/combustion pressure / temperature
  → up to 160 bar max. 240 bar / 700 ... >1000 K
- Variation of flow/turbulence by speed: u'≈ 3...6 m/s (300...1000 rpm)

Operating conditions:

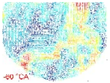
p

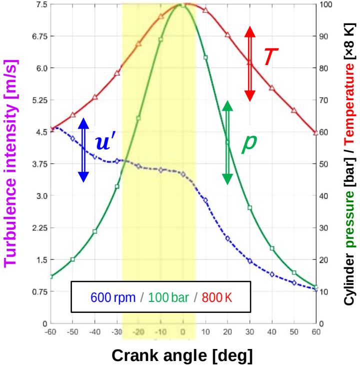


T



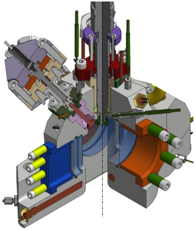
flow

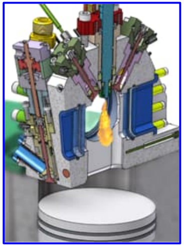




Test Facility "Flex-OeCoS"

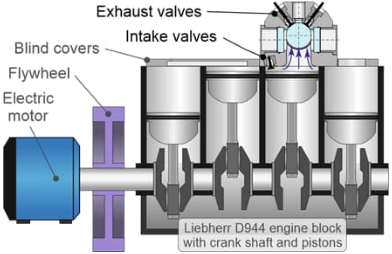
Principle, specifications and features



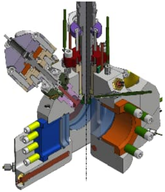


Optical combustion chamber

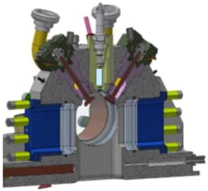
- Optical access: 4 windows optical chamber ⦸ 60×20 mm
- Engine-like compression/combustion pressure / temperature
  → up to 160 bar max. 240 bar / 700 ... >1000 K
- Variation of flow/turbulence by speed: u'≈ 3...6 m/s (300...1000 rpm)
- Flexible operation: mixture charge, injection parameter, timing, ...
- Variability to adapt test rig to a variety of DF combustion processes



low pressure

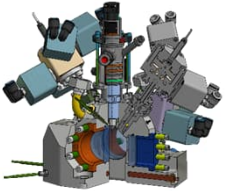


pilot spray



prechamber jet

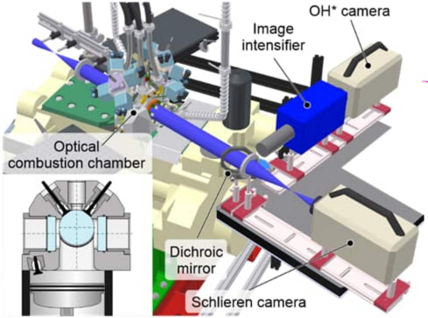
high pressure



gas injector

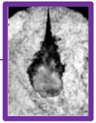
Characterization DF Combustion Processes

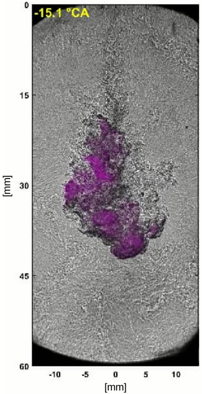
Lean-premixed pilot fuel ignited dual-fuel combustion

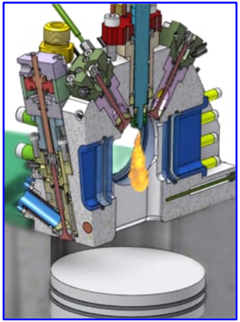


OH* CL

Schlieren

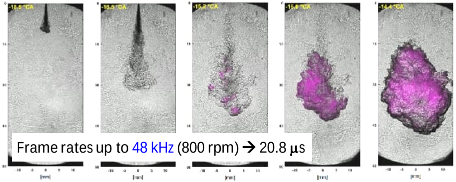






D. Humair, et al.: "Characterization of dual-fuel combustion processes", 6th Rostock Large Engine Symposium 2020

Simultaneous Schlieren / OH* chemiluminescence



Investigations

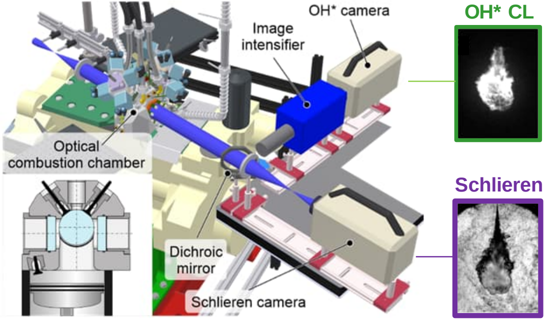
→ Ignition delay (location): OH* chemiluminescence

→ Flame propagation: Schlieren

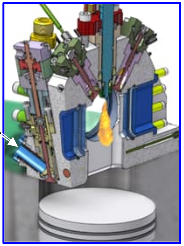
→ Heat release/cyclic stability: pressure measurements

Initial NH_3 Combustion Tests

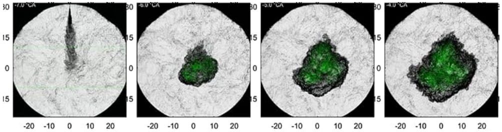
Experimental setup / operation parameter variation



- Gaseous NH_3/air charge
- Pilot fuel ignition (dodecane)
- Operation parameter variation:
  - ➢ air/fuel ratio
  - ➢ pressure
  - ➢ temperature
  - ➢ flow conditions
  - ➢ start/duration of injection



Simultaneous Schlieren / OH* chemiluminescence



NH_3 combustion characteristics

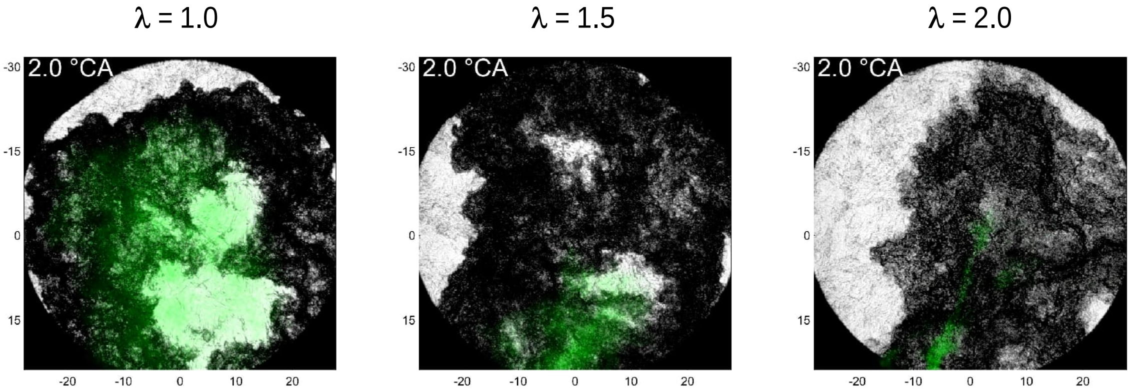
→ Ignition delay (location): OH* chemiluminescence

→ Flame propagation: Schlieren

→ Heat release/cyclic stability: pressure measurements

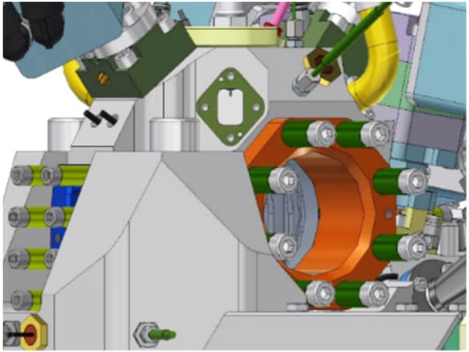
Variation of air/fuel ratio λ (mixture charge)

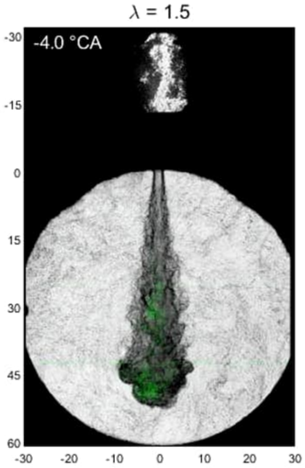
p_{comp} = 70 bar / T ≈ 810 K / SOI = -10 deg / ET = 500 μs



Initial NH_3 Combustion Tests

Pre-Chamber reactive jet





p_compr = 70 / 100 bar

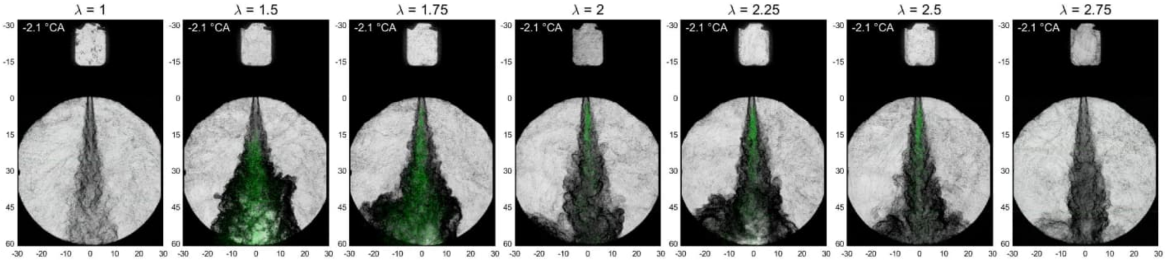
T_gas = 50°C / 100°C

Variation of: λ, SOI (spark plug), λ_pre-chamber

Initial NH_3 Combustion Tests

Lambda variation

SOI = -10°CA **70 bar, 50°C**



Summary

The fuel mix has evolved considerably already since the 2014 AMF report release

The development of dual-fuel technology acts as an enabler for the adoption of fuels beyond the traditional liquid fossil fuels

DF engines developed for LNG-fuelled applications are already today capable of using renewable methane from either synthesis or biogenic sources

Engine developers have started extensive programs in order to be able to deliver products to the market that can operate safely and efficiently on renewable methanol and ammonia

First methanol engines are already in operation, the rollout to a larger portfolio as well as the development of new products for methanol and ammonia follows an ambitious schedule

Thank you!