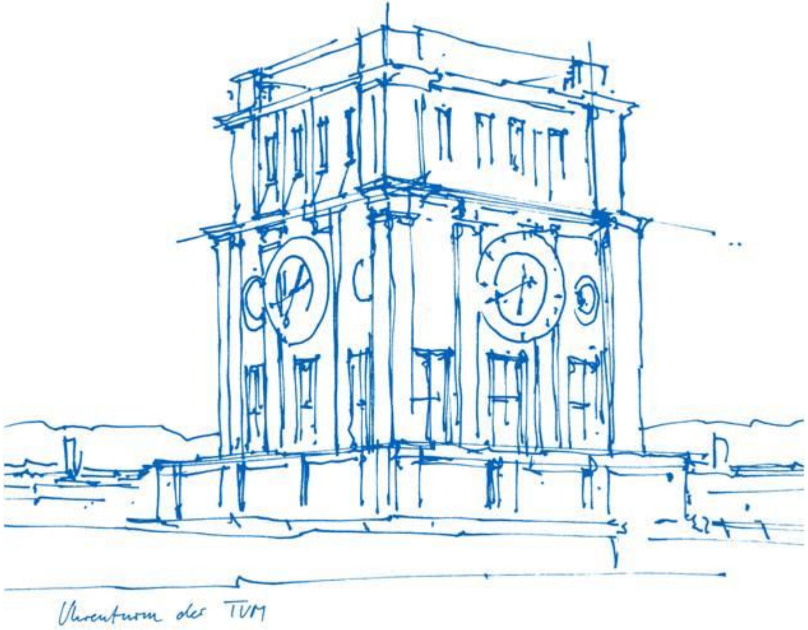
Ammonia as a fuel for high-pressure direct injection combustion in marine engines

NETL Ammonia Combustion Technology Group Meeting

05.03.2024

Valentin Scharl and Thomas Sattelmayer
Technische Universität München
School of Engineering and Design
Chair of Thermodynamics

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag



Agenda

- **Ammonia as a marine fuel**
- The AmmoniaMot consortium
- Ammonia combustion research at TUM
- Summary and conclusions

Ammonia is one option to decarbonize long-range shipping

	H_2	syn. CH_4	MeOH	**NH_3**
energy density	−	+	++	+
storability	−	0	++	+
transportation cost	−−	++	++	+
CO_2 emissions (tank to wake)	++	−	−−	++
risk of other GHG	+	−	++	0
retrofitability (shipping)	0	0	++	−

Source: [3]

→ N_2O

→ Space requirements

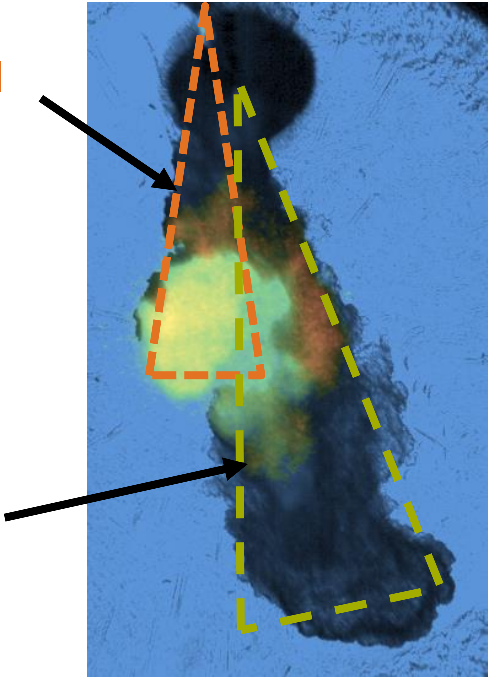
- No retrofit of currently existing vessels with ammonia
- Vessel lifetime > 30y

→ Suitable ammonia engines, fuel systems and vessels need to be developed now!

The HPDF combustion is promising for NH_3

- Spray combustion via diesel process
- High ignition energy by diesel pilot
- No knocking, no throttle losses, less near-wall quenching
- Diesel-only operation possible

→ Proof of concept required



Agenda

- Ammonia as a marine fuel
- **The AmmoniaMot consortium**
- Ammonia combustion research at TUM
- Summary and conclusions

The AmmoniaMot project progresses ammonia‘s introduction as a marine fuel

NEPTUN SHIP DESIGN

- Fuel system
- Requirements & regulations

MAN Energy Solutions

- Engine design
- Technology transfer

AMMONIAMOT

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing

TUM

- Fundamental combustion research
- CFD code development

WOODWARD L'orange

- HPDF injector development

The AmmoniaMot project progresses ammonia‘s introduction as a marine fuel

NEPTUN SHIP DESIGN

- Fuel system
- Requirements & regulations

MAN Energy Solutions

- Engine design
- Technology transfer

NH3 AMMONIAMOT

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing

TUM

- Fundamental combustion research
- CFD code development

WOODWARD L'orange

- HPDF injector development

The HPDF combustion process in 4-stroke engines requires new injector developments

- Multi-needle injector
- High volume flux requirements for ammonia
- Space constraints in 4-stroke engines

WOODWARD L'orange

- HPDF injector development

The AmmoniaMot project progresses ammonia‘s introduction as a marine fuel

NEPTUN SHIP DESIGN

- Fuel system
- Requirements & regulations

MAN Energy Solutions

- Engine design
- Technology transfer

NH_3 AMMONIAMOT

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing

TUM

- Fundamental combustion research
- CFD code development

WOODWARD L'orange

- HPDF injector development

The combustion process is optimized in a single-cylinder engine

- High-speed single-cylinder engine
- Testing of various injectors and operating strategies, e.g. injection timing, piloting strategy
- Optimization regarding
  - Engine efficiency,
  - Ammonia fuel share
  - Combustion stability
  - Exhaust emissions (N_2O, NO_x, NH_3)

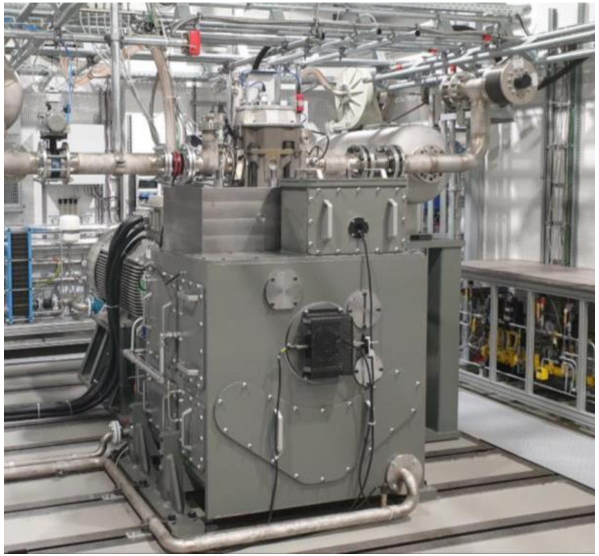
Single-cylinder research engine FM18

Parameter	Unit	Value
Stroke	mm	215
Bore	mm	175
Number of cylinders	-	1
Piston displacement	dm³	5.17
Con rod length	mm	547
Rated power	kW	180
Rated speed	min^{-1}	1800
Number of valves	-	4
Compression ratio	-	19.2:1 (variable)
Camshaft	-	Axially tensioned (variable)

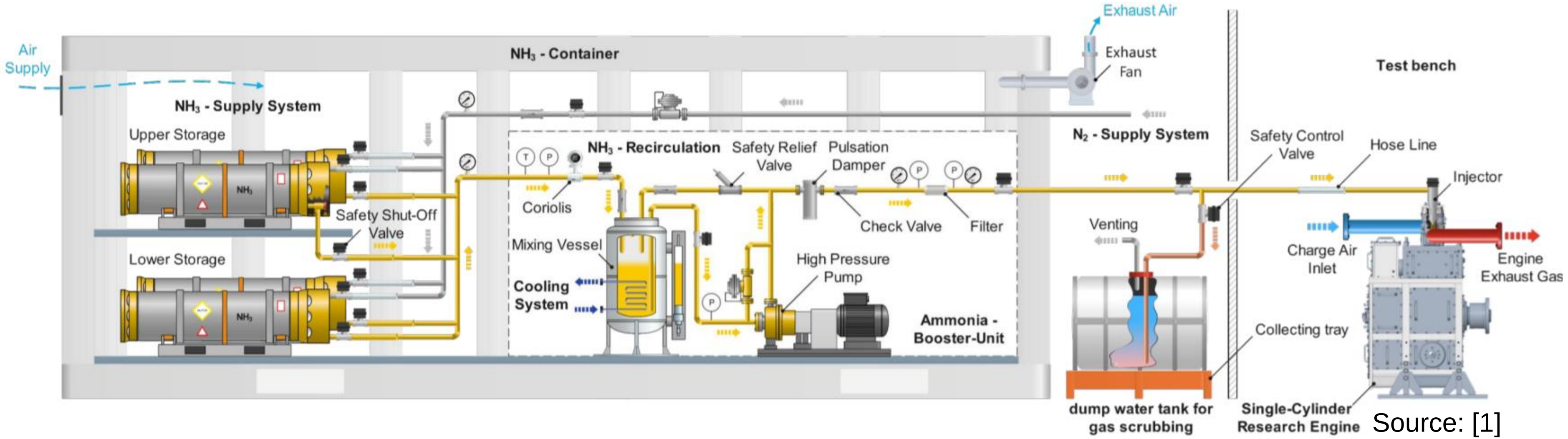
Source: [1]

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing



Ammonia supply system for the single-cylinder engine



Source: [1]

- Pressurized tanks (N_2 cushion) supply liquid ammonia
- A piston pump provides injection pressures of up to 500 bar
- Safety measures: shut-off valves, nitrogen purging, dump tank, gas warning, protective equipment

WTZ INNOVATIVE SCIENCE & RESEARCH   NK NEPTUN SHIP DESIGN

The AmmoniaMot project progresses ammonia‘s introduction as a marine fuel

NEPTUN SHIP DESIGN

- Fuel system
- Requirements & regulations

MAN Energy Solutions

- Engine design
- Technology transfer

NH_3 AMMONIAMOT

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing

TUM

- Fundamental combustion research
- CFD code development

WOODWARD L'orange

- HPDF injector development

The obtained knowledge is transferred to MAN‘s medium-speed engines

MAN Energy Solutions

- Supply of engine components and knowledge for single-cylinder experiments
- CFD code validation using TUM and WTZ experimental data
- Transfer project results to medium-speed engine concept
  - → Injectors WOODWARD L'orange
  - → Engine components
  - → CFD

The AmmoniaMot project progresses ammonia‘s introduction as a marine fuel

NEPTUN SHIP DESIGN

- Fuel system
- Requirements & regulations

MAN Energy Solutions

- Engine design
- Technology transfer

NH_3 AMMONIAMOT

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing

TUM

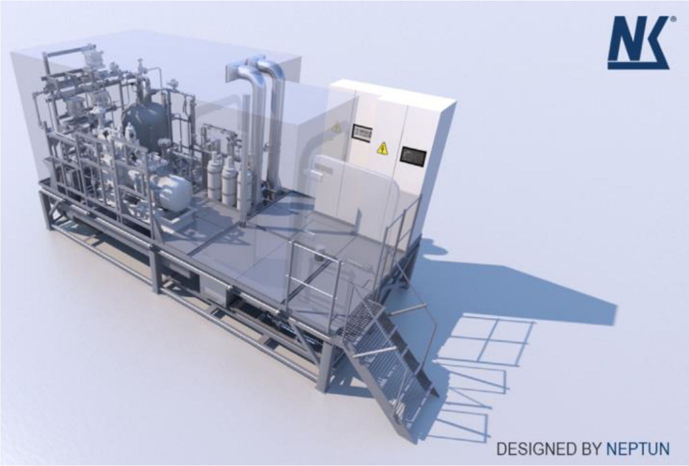
- Fundamental combustion research
- CFD code development

WOODWARD L'orange

- HPDF injector development

The on-board ammonia system requires new designs and certifications

NEPTUN SHIP DESIGN



- Development of modular, containerized ammonia module: CAPSAM

→ increased safety, lower cost, easier certification, low space requirements

- Risk analysis and mitigation strategies in cooperation with ABS-Houston ABS

- Concept for integration of fuel system into vessels

- Support of maritime regulation adjustments

The AmmoniaMot project progresses ammonia‘s introduction as a marine fuel

NEPTUN SHIP DESIGN

- Fuel system
- Requirements & regulations

AMMONIAMOT

TUM

- Fundamental combustion research
- CFD code development

MAN Energy Solutions

- Engine design
- Technology transfer

WOODWARD L'orange

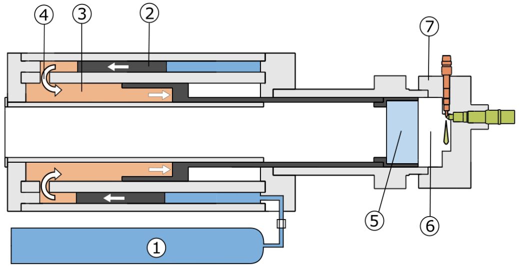
- HPDF injector development

WTZ INNOVATIVE SCIENCE & RESEARCH

- Engine testing

TUM conducts fundamental experiments and CFD simulations

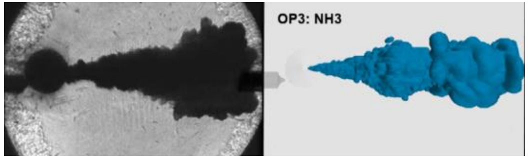
- Feasibility studies and injector design guidelines



Single-shot engine experiments reacting & inert

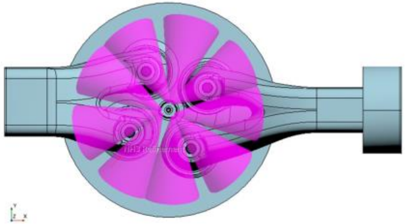
- Improve understanding of ammonia spray combustion behavior

CFD validation



MAN Energy Solutions

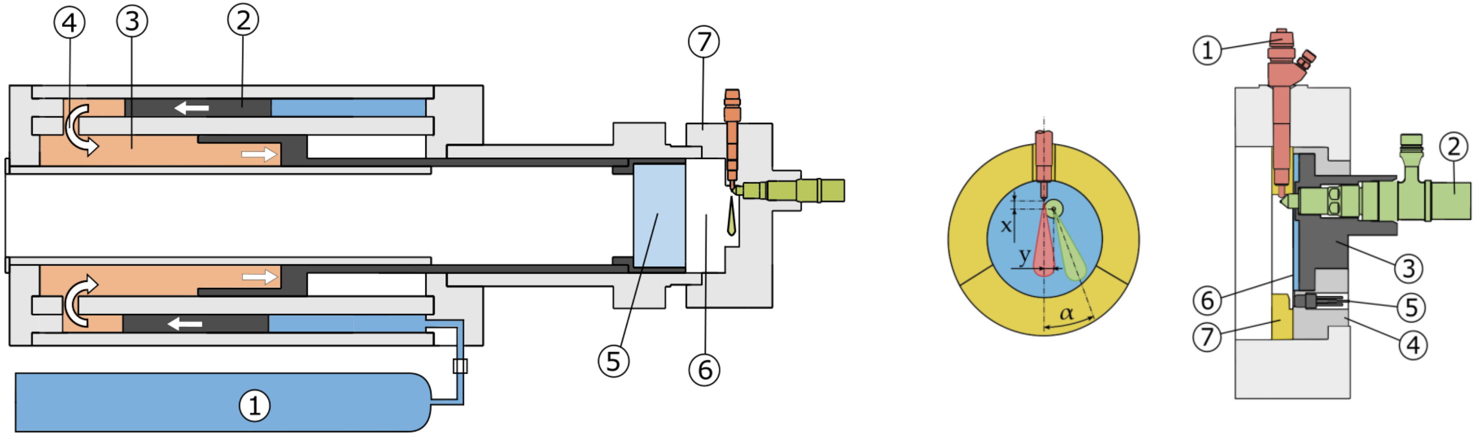
Engine simulations
→ RANS, detailed chemistry



Agenda

- Ammonia as a marine fuel
- The AmmoniaMot consortium
- **Ammonia combustion research at TUM**
- Summary and conclusions

Experiments are conducted in a single-shot engine



- ~ 1000 rpm
- 200 mm bore

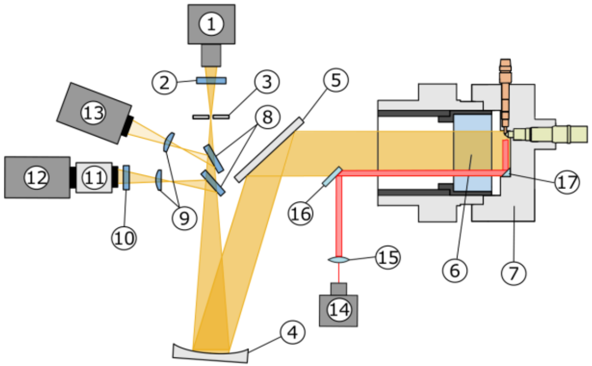
- TDC temperature: 780-920 K
- TDC pressure: 75-125 bar

- Single hole injectors
- Injection pressures: 560 bar (NH_3), 2000 bar (Diesel)

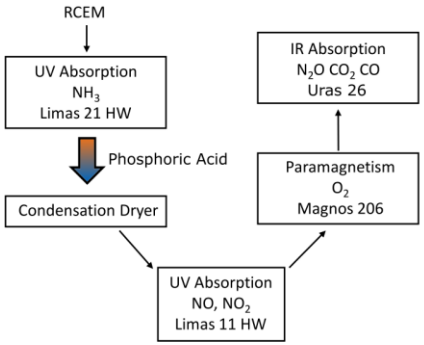
Measurement techniques

- **Optical measurement techniques:**

→ Shadowgraphy, OH*-CL, Mie-scattering, Spectroscopy, Natural lum.

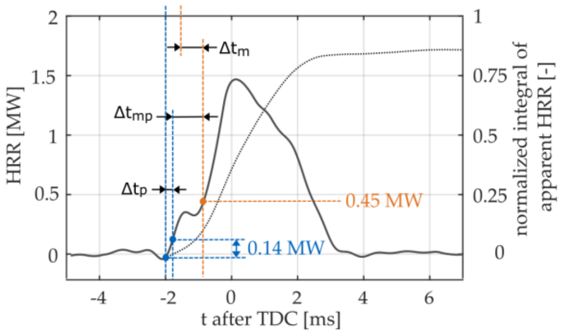


- **Exhaust gas analysis**



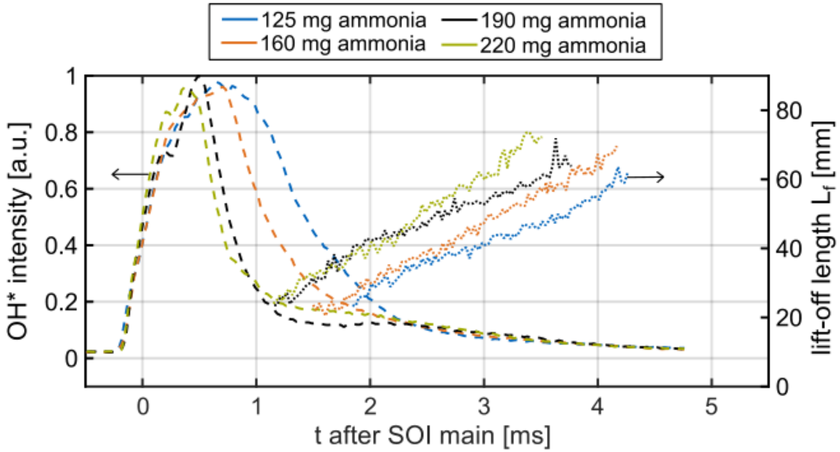
- **Heat release rate (HRR) analysis**

→ Thermodynamic modeling

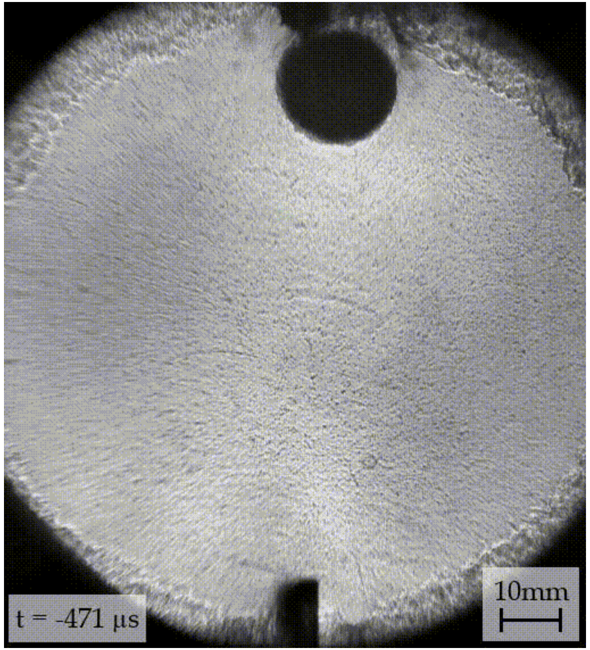


Ammonia spray flames can fail to stabilize

- Slow drift-off
- No „combustion recession“ or „flashback“
- 920 K, 125 bar

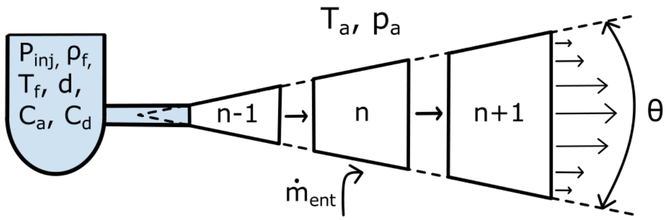


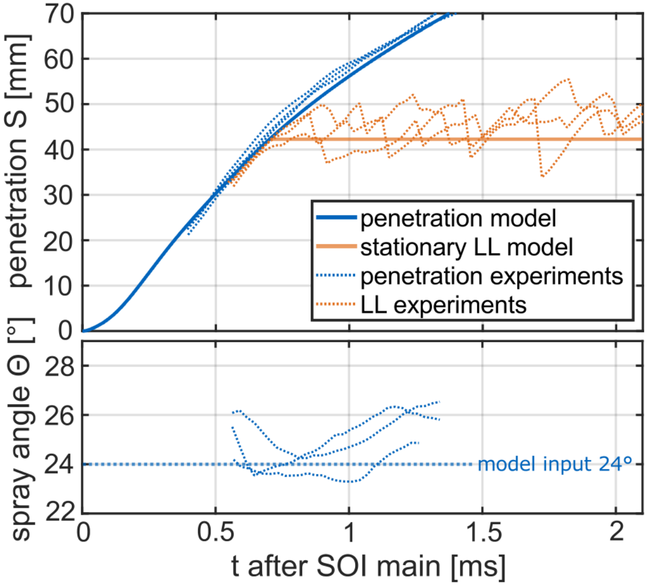
Shadowgraphy + OH*-CL



A 1-D spray model is validated using inert spray data

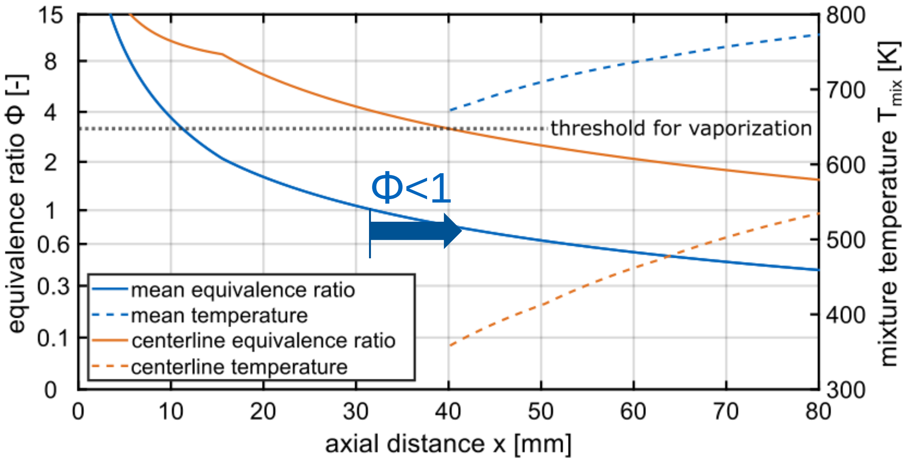
- Optical spray angle as input
- Validation via gaseous and liquid penetration (Shadowgraphy + Mie-Scattering)





The spray model reveals low temperatures and equivalence

- Extremely low temperatures
- Fast lean-out
- Φ<1 upstream of liquid length

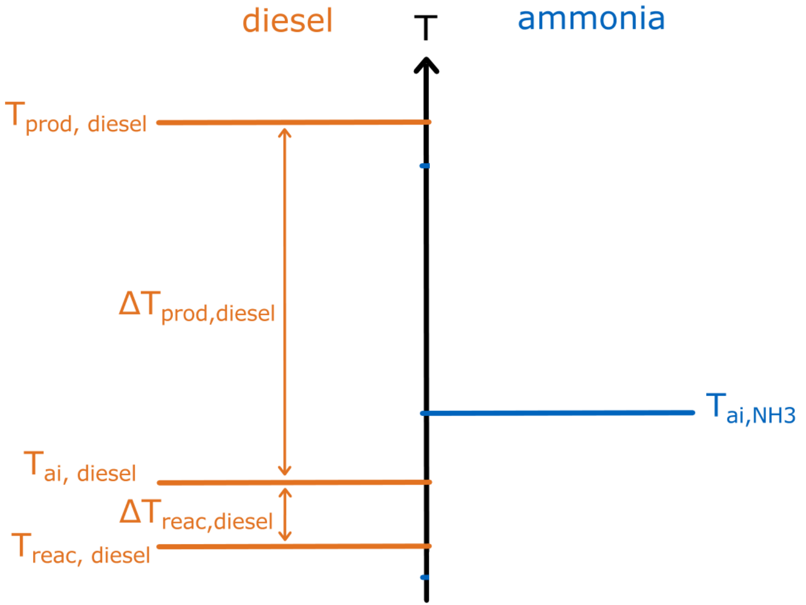


Mixing requirements with combustion products to undergo auto-ignition are high in ammonia sprays

- High auto-ignition temperature

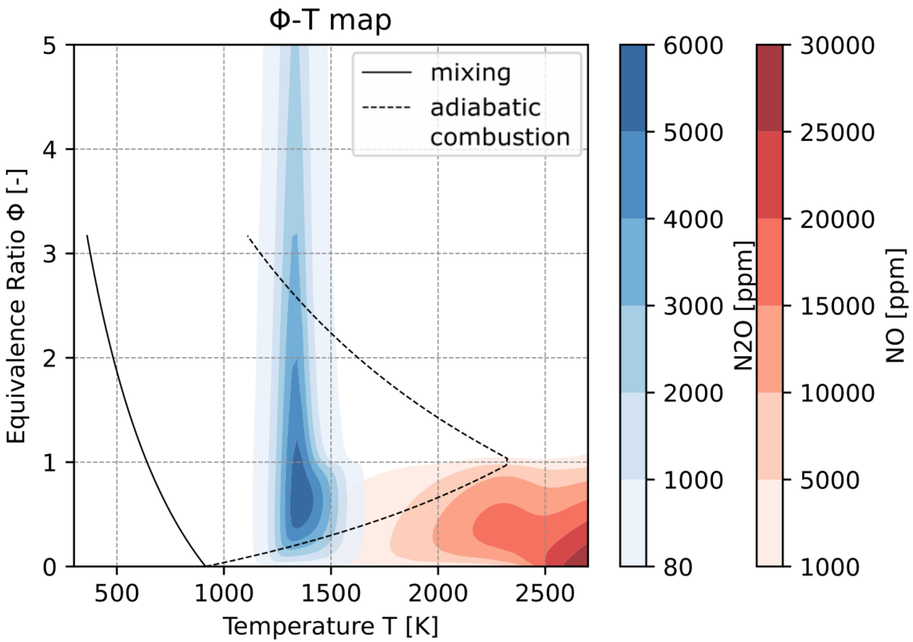
(1) Upstream: Low reactant temperatures
  - High enthalpy of vaporization

(2) Downstream: Low product temperatures
  - Lean combustion



Lean conditions increase NO and N_2O formation

- NO forms under lean conditions
- N_2O results from incomplete combustion, e.g. due to very lean conditions
- Low air pollutant formation for slightly fuel-rich conditions



Drifting flame causes lean conditions!

Large marine engines facilitate ammonia spray combustion

- High compression ratios

→ Auto-igniting conditions at high loads

- Long residence times

→ Reduced N_2O formation and NH_3 emissions

- Exhaust gas after treatment and fuel handling feasible

Promising results of 4-stroke single-cylinder engine @ WTZ

- Ammonia LHV share > 95%
- Ammonia-NOx-Ratio < 1
- N_2O emissions < 10 ppm

→ GHG reduction > 90%

Lehrstuhl für Thermodynamik
TUM School of Engineering and Design
Technische Universität München

Agenda

- Ammonia as a marine fuel
- The AmmoniaMot consortium
- Ammonia combustion research at TUM
- **Summary and conclusions**

Summary and Conclusions

- AmmoniaMot takes a holistic approach toward establishing ammonia as a marine fuel

- Ammonia sprays show low temperatures and flame stabilization may fail

→ Increased NO and N_2O formation

- Suitable combustion processes for ammonia differ from established low-temperature combustion processes

- Large heavy duty engines are suitable for overcoming ammonia's combustion challenges

AmmoniaMot 2: Comparison of diffusive and homogenous ammonia combustion processes

Thank you for your attention!

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Bibliography

[1] K. Stenzel, H. Arndt, P. Thorau, V. Scharl, T. Sattelmayer, Ammoniamot - experimental investigations of an ammonia dual-fuel combustion process for decarbonization of the maritime sector, in: The future of large engines, Forschungszentrum für Verbrennungsmotoren und Thermodynamik Rostock GmbH, Rostock, Germany, September 2022.
[2] D. Krnac, B. Manickam, P. Holand, V. Scharl, T. Sattelmayer, Ammonia-diesel dual-fuel combustion simulation using a tabulated chemistry approach, in: 19th Symposium Sustainable Mobility, Transport and Power Generation, Graz, Austria, 2023.
[3] C. Kunkel, NH3 – as shipping fuel for 4-stroke Engines, 11th Int. Conf. Fuel Science - Ammonia as future fuel, RWTH Aachen, Aachen, Germany, May 2023
[4] P. Thorau,K. Stenzel, T. Tolubajew, C. Reiser, B. Buchholz: Entwicklung eines HPDF-Ammoniak-Brennverfahrens für schnelllaufende Schiffsmotoren. 12. Tagung Einspritzung und Kraftstoffe, 2023
[5] V. Scharl, T. Sattelmayer, Ignition and combustion characteristics of diesel piloted ammonia injections, Fuel Communications 11 (2022) 100068. doi:10.1016/j.jfueco.2022.100068.
[6] V. Scharl, T. Lackovic, T. Sattelmayer, Characterization of ammonia spray combustion and mixture formation under high-pressure, direct injection conditions, Fuel 333 (2023) 126454. doi:10.1016/j.fuel.2022.126454.
[7] V. Scharl, T. Sattelmayer, Spectroscopic investigation of diesel-piloted ammonia spray combustion, Fuel 358 (2024) 130201. doi:10.1016/j. fuel.2023.130201.
[8] V. Scharl, T. Sattelmayer, Investigation of post-injections for emission reduction of diesel-piloted ammonia spray combustion, in: 30th CIMAC Congress Busan, 2023.