Session: ICE – H_2 and NH_3 Combustion

Advanced Ammonia Combustion Process Development for Maritime Applications

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Abstract

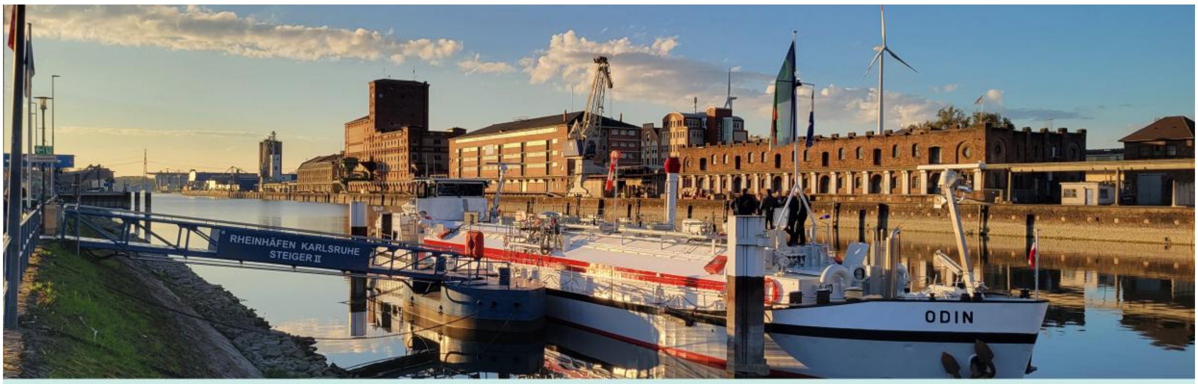
The urgent need to reduce CO_2 emissions in all areas demands the swift development and implementation of appropriate solutions for the worldwide shipping branch both for sea-going and inland waterway vessels. Green ammonia, produced from renewable energies, represents one of the few carbon-free fuels with realistic large-scale implementation potential. Despite its promising characteristics, the inherently low reactivity of ammonia poses challenges for engine ignition stability and complete combustion, which has so far prevented its use as a stand-alone fuel in internal combustion engines. As a result, dual-fuel strategies with hydrogen or diesel are typically required, increasing system complexity and fuel infrastructure demands on board.

As part of this work, two different ammonia-based combustion concepts were developed, implemented, and systematically investigated with the overarching goal of maximizing the energetic ammonia share while minimizing the required pilot energy. The first concept is based on a spark-ignited NH_3–H_2 combustion process with variable hydrogen fractions ranging from small ignition-support quantities up to pure ammonia operation. The second concept relies on a dual-fuel diesel pilot combustion process in which highly premixed ammonia–air mixtures are ignited by a small quantity of Diesel-pilot-fuel.

To investigate these concepts, a Liebherr D966 single-cylinder engine was installed on the test bench of the Institute of Internal Combustion Engines (IFKM). The setup included comprehensive thermodynamic, optical, and emissions analytics, enabling detailed assessment of mixture formation, ignition behaviour, and pollutant formation. A major outcome of the study is the demonstration that, with an optimized ignition system and tailored mixture formation concepts, stable 100% ammonia combustion can be achieved across the entire load range of the engine. This represents a substantial step forward, as it allows a significant downsizing of the onboard infrastructure.

The work is closely linked to ongoing activities within the German Campfire alliance, where a complete ammonia-fueled cracker-engine-unit is being developed as a propulsion solution for inland waterway vessels. The findings of the present single-cylinder study form the technological foundation for transferring the combustion concept to the multi-cylinder engine, which will subsequently be tested under maritime boundary conditions together with the cracker and an adapted exhaust aftertreatment system.

Overall, the results highlight the feasibility and potential of ammonia as a fuel for future maritime engine propulsion systems. Both the spark-ignited NH_3–H_2 concept and the diesel-pilot dual-fuel approach offer viable pathways for new engine developments as well as retrofit solutions for existing diesel engines, supporting the transition towards sustainable, carbon-free shipping.



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WKM Symposium 17.03.2026

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Agenda

1. Introduction to the Campfire alliance
2. Ammonia as fuel
3. Ammonia-based propulsion concept
4. Combustion process development
5. Summary and outlook

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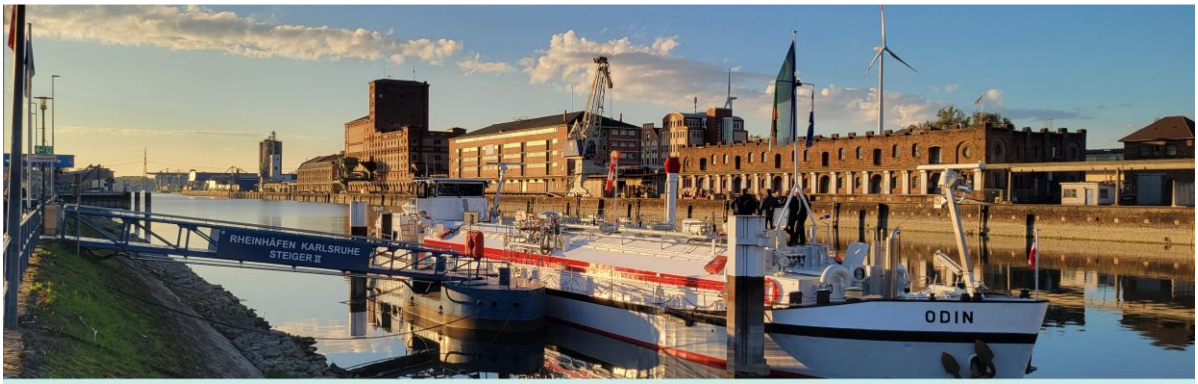

Introduction to the Campfire alliance

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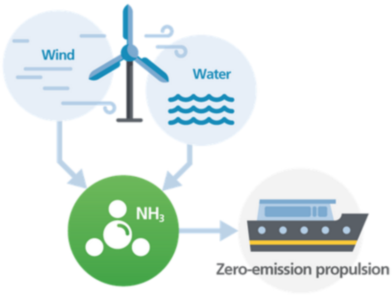
Introduction to the Campfire Alliance

Ammonia-based energy technologies

- Decentralised production of green ammonia from air, water and renewable energy
- Use in zero-emission drives in maritime mobility and the energy industry
- Technical solutions for ammonia import and ammonia farming in the region
- Logistics and infrastructure for distribution



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wir! Wandel durch Innovation in der Region

Leitprojekt TransHyDE

https://wir-campfire.de/

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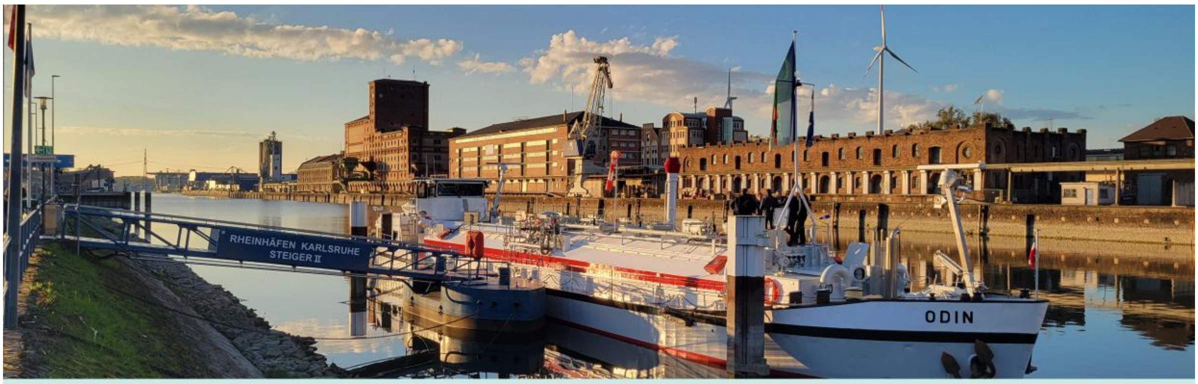

Ammonia as fuel

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Ammonia as Fuel

Fuel properties in comparison

		NH_3	H_2	Methanol	Natural gas	Diesel fuel
Volumetric calorific value (20 °C)	MJ/l	12.68 (9 bar)	2.85 (350 bar)	15.8	9.07 (250 bar)	35.14
Stoichiometric air demand	kg/kg	6.1	34.3	7.14	17.2	14.5
Min. auto-ignition temperature	°C	650	520	464	630	180-320
Max. laminar flame speed	m/s	0.07	2.91	0.45	0.37	≈0.4
Adiabatic flame temperature	°C	1,800	2,110	1,970	1,950	2,327
Min. ignition energy	mJ	14	0.016	0.2	0.28	

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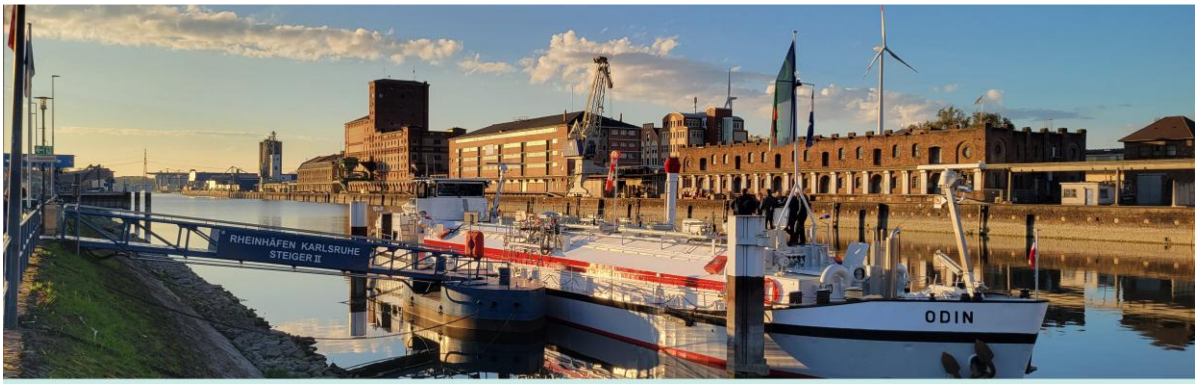

Ammonia-based propulsion concept

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Ammonia-based Propulsion Concept

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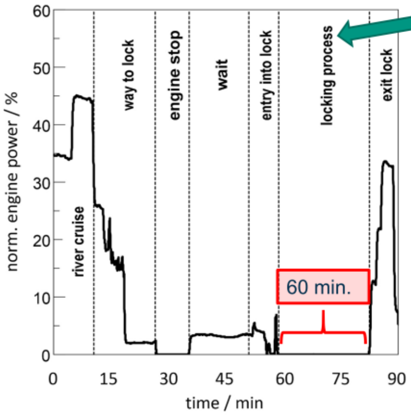
Load Profile of MS ODIN



Engine switched off or is at very low load during lock manoeuvre

Driving profile well-suited for hybrid operation

Battery charging or full electric drive possible

Power demand is typically lower compared to a sea-going vessel

Cracker Development

H_2 supply:

$NH_3 \rightarrow H_2 + N_2$ (+ residual NH_3)

Cracker boundary conditions:

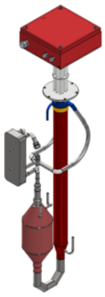
Max. cracker H_2 output ≈ 4.5 kg/h

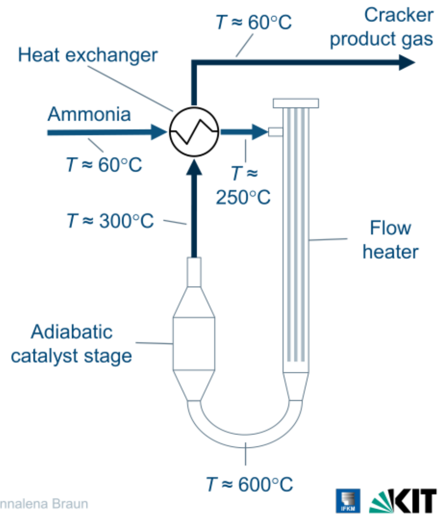
Product gas: 6–8 bar, < 60 °C

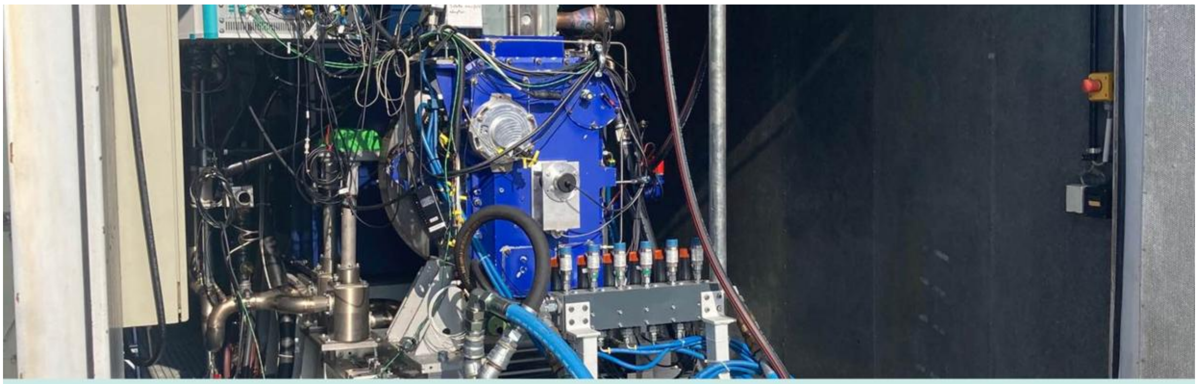
Development tasks:

Complete cracker module incl. reactor, heat exchanger, insulation, controls

Commissioning & testing with digital twin for dynamic simulation & optimization







Combustion Process Development

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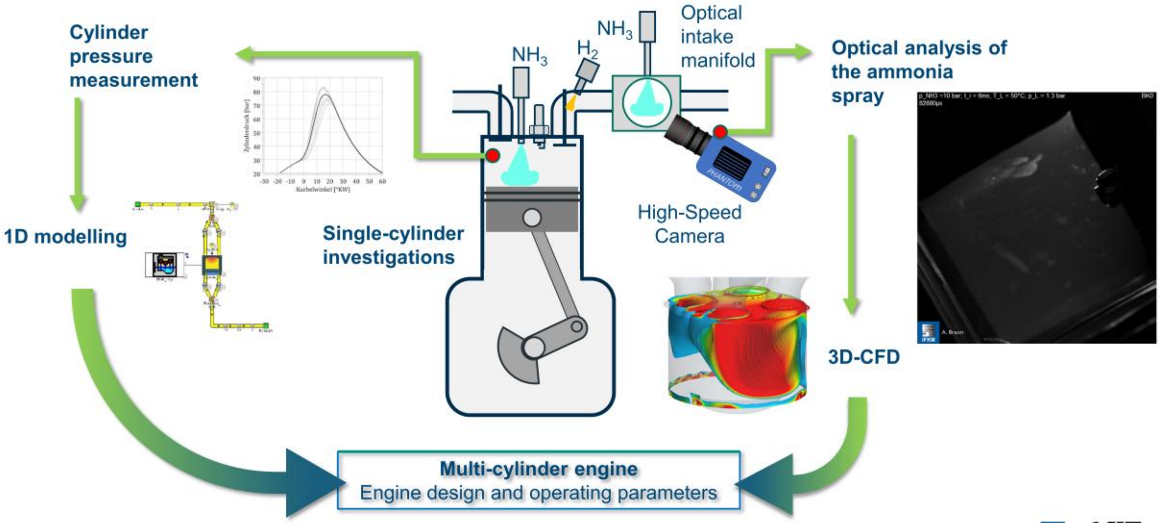
Development Methodology



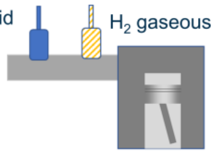
Combustion Process Development

Objectives of the combustion process development

- High energetic NH_3 share
- Wide range of NH_3-H_2 mixing ratios
- Stable combustion:
  - COV of IMEP below 3 %
  - Pre-ignition and Knock-free operation

Approach

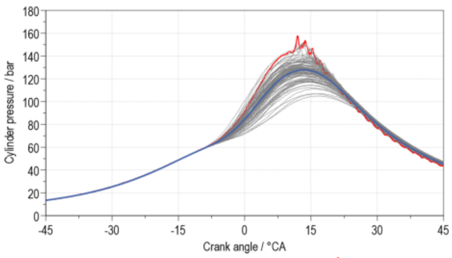
- Determination of the maximum and minimum energetic NH_3 share
- Limitation by knock limit and combustion stability

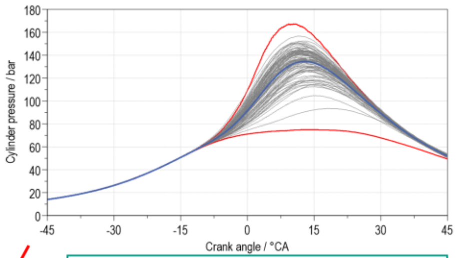


Description	Value
Cylinder	1
Stroke	157 mm
Bore	135 mm
Max. Speed	1900 rpm
Operating principle	4-stroke SI
Displacement	2,24 l
Base Engine	Liebherr D966

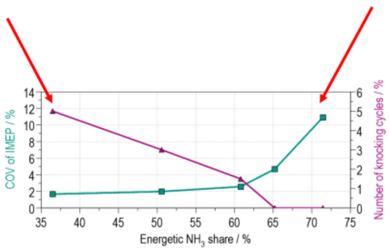
Combustion Process Development

Termination Criteria





If the H_2 share is too high, the knocking tendency increases.
Knock evaluation: Mannesmann method



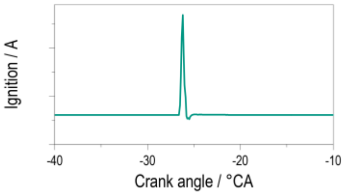
If the NH_3 share is too high, the Combustion becomes more unstable.

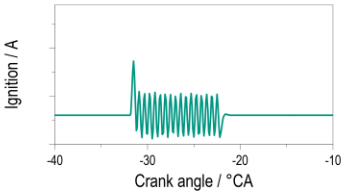
Termination criteria:
Max. ex. gas temperature = 650 °C
Max. peak pressure = 220 bar

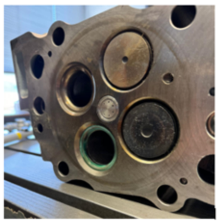
Combustion Process Development

Variation of the Ignition System

Conventional ignition system	High energy capacitive ignition system	Passive prechamber sparkplug







Goal of the measurements:

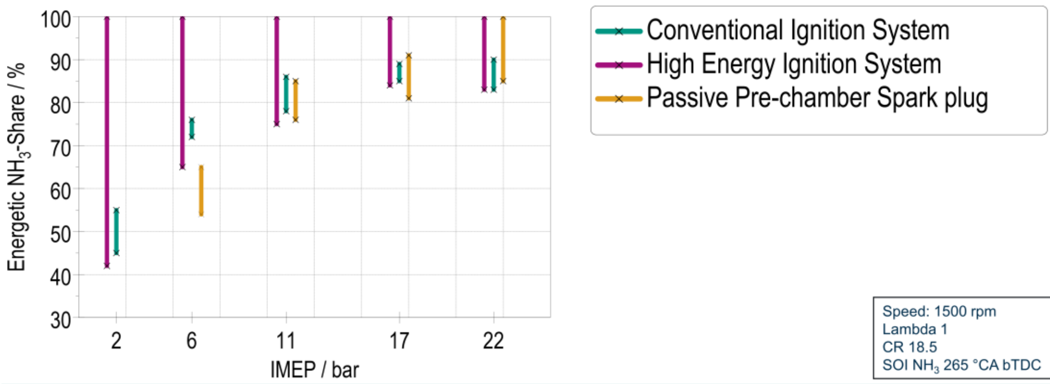
Which system allows **maximum energetic NH_3 share**?

Is an **operation without hydrogen** possible?

How is the influence on the **emissions**?

Combustion Process Development

Variation of the Ignition System



Speed: 1500 rpm
Lambda 1
CR 18.5
SOI NH_3 265 °CA bTDC

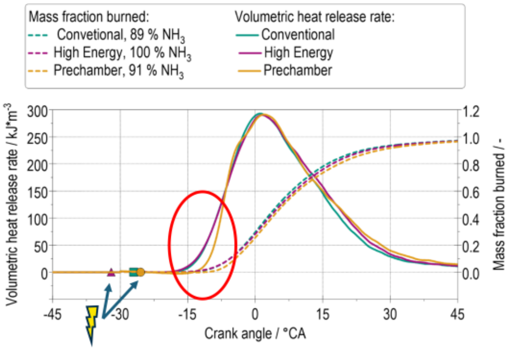
Most beneficial configuration: **High energy ignition system** with the J-gap spark plug.

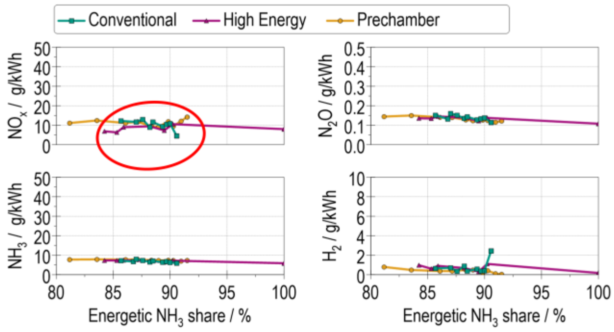
→ allows **100 % NH_3 operation in every load point**

Combustion Process Development

Variation of the Ignition System

Speed: 1500 rpm
Load: 17 bar IMEP
Lambda 1
CR 18.5
SOI NH_3 265 °CA bTDC



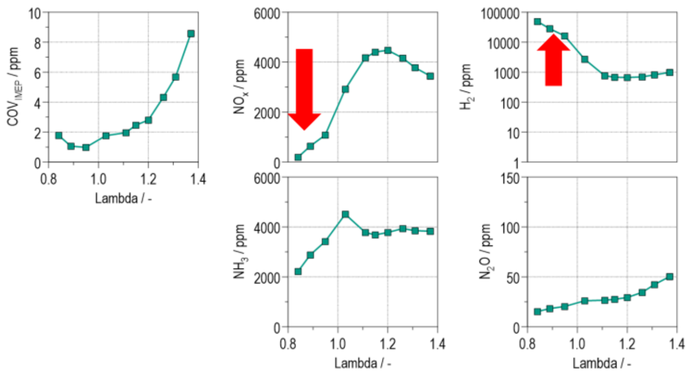


→ Longer ignition delay with pure NH_3, but similar burn duration as H_2-assisted combustion
→ Emissions largely unaffected by ignition system
→ Strong emission dependence on lambda

Combustion Process Development

Lambda Variation

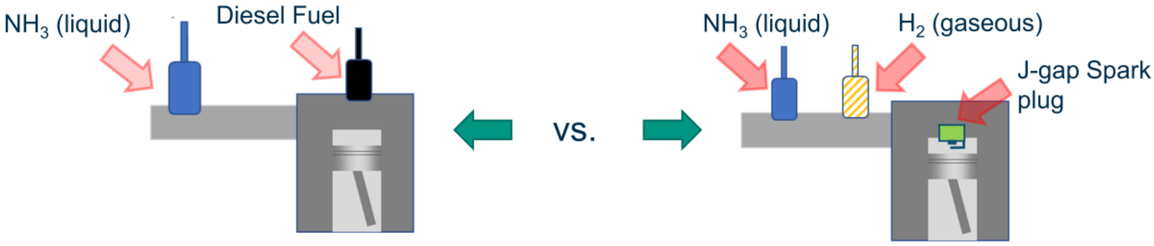
1500 rpm
CR 18.5
100 % energetic NH_3 share
17 bar IMEP
H.E. ignition system



→ The Combustion Process remains stable between **0.94 < λ < 1.2.**
→ The COV of IMEP has the lowest value at **λ close to 1**
→ **λ > 1** leads to increasing **NOx emissions.**
→ **λ < 1** leads to a massive increase of **H_2 Emissions** and a **decrease of NH_3 emissions**.

Combustion Process Development

Diesel Fuel + NH_3 Combustion vs. H_2 + NH_3 Combustion



<u>Goal of the measurements:</u>

How high is the possible energetic NH_3 share with Diesel-pilot fuel injection?

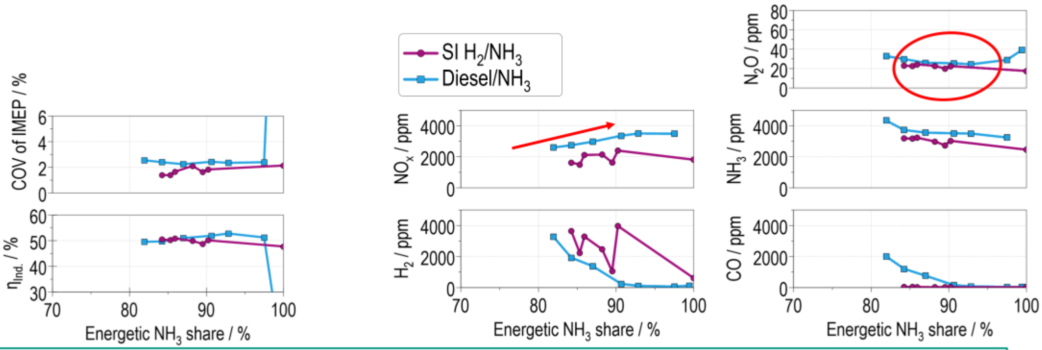
How is the influence on the emissions?

How high is the efficiency of the Diesel-fuel compared to the SI H_2 +NH_3 combustion?

Combustion Process Development

Diesel Fuel + NH_3 combustion vs. H_2 + NH_3 Combustion

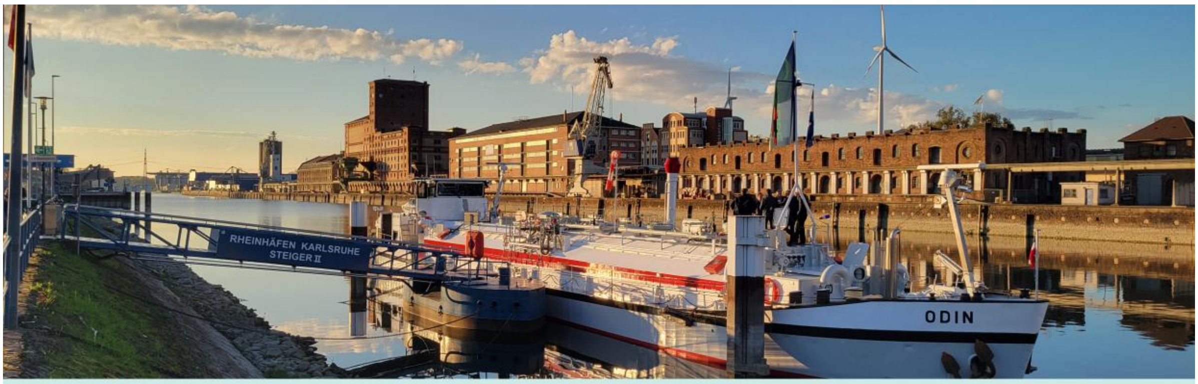
Speed: 1500 rpm
Load: 17 bar IMEP
Lambda 1 and 1.1
CR 18.5
SOI NH_3 265 °CA bTDC



→ Diesel pilot enables up to 97 % NH_3 energy share; SI allows 100 % NH_3 combustion

→ NO_x emissions rise with higher NH_3 share

→ N_2O emissions remain similar across both combustion modes



Summary & Outlook

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Summary

Variation of the Ignition System:

- **Ignition energy** is crucial for stable NH_3 combustion
- **100 % NH_3 operation** possible at all load points with high energy ignition system
- **High compression ratio** supports pure NH_3 operation
- Liquid NH_3 port fuel injection enables **Diesel-like efficiency** and **engine performance**

Diesel Fuel Ammonia combustion:

- Up to **97 % energetic NH_3 share** in Diesel-dual-fuel mode

Emissions:

- N_2O Emissions on a low level
- **High NO_x raw emissions** at engine outlet but…
  …NH_3 slip and lambda 1 enables **3-way catalytic converter** for NO_X reduction

Outlook

Further measurement should address:

- High-pressure NH_3 direct injection
- Exhausgas aftertreatment systems

The combustion process will be transferred to the multi-cylinder engine

The multi-cylinder engine will be operated at the Campfire Open Innovation Lab (COIL) close to Rostock/Germany

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