

Improving ammonia combustion characteristics through partial premixing in porous burners

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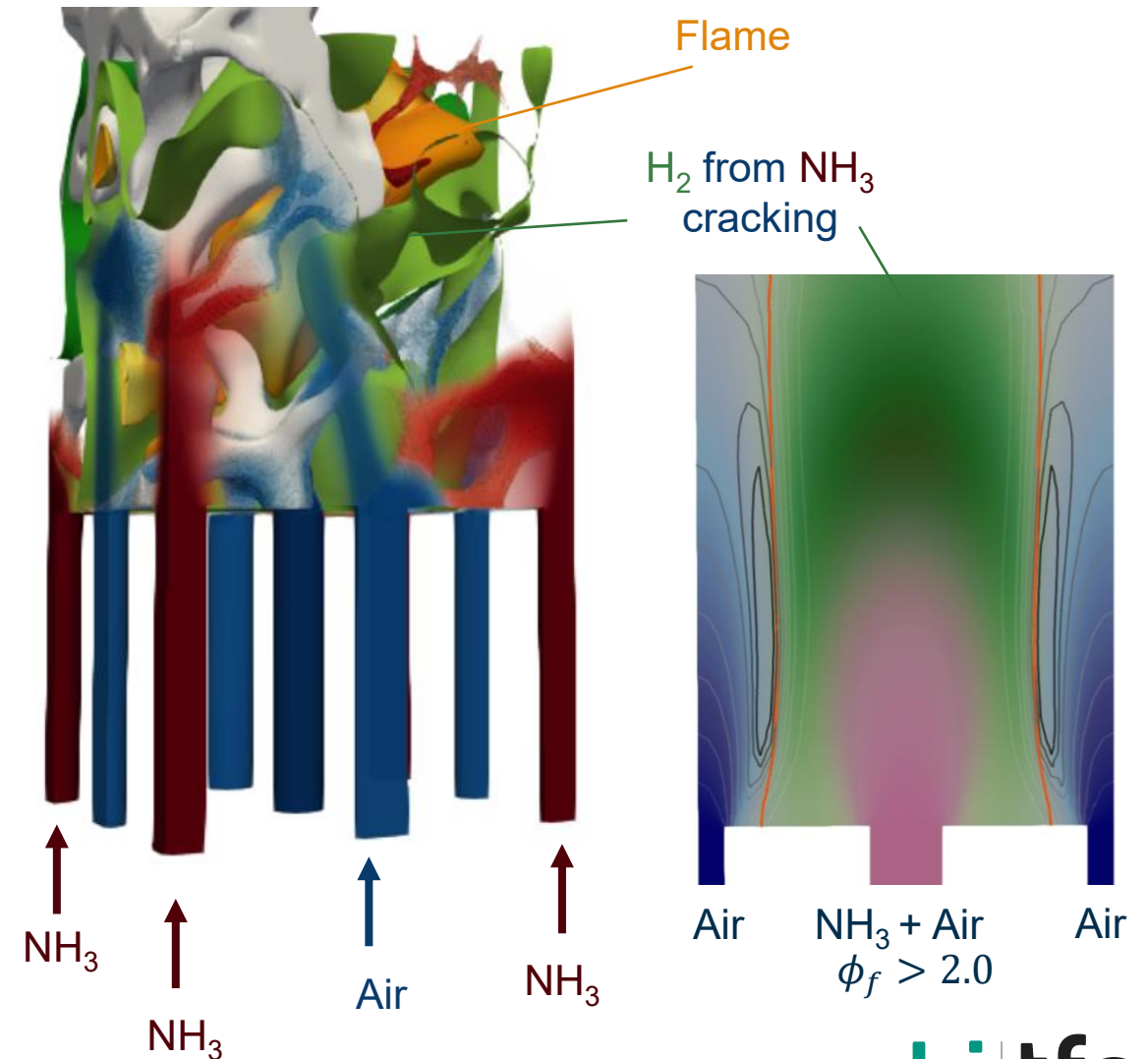
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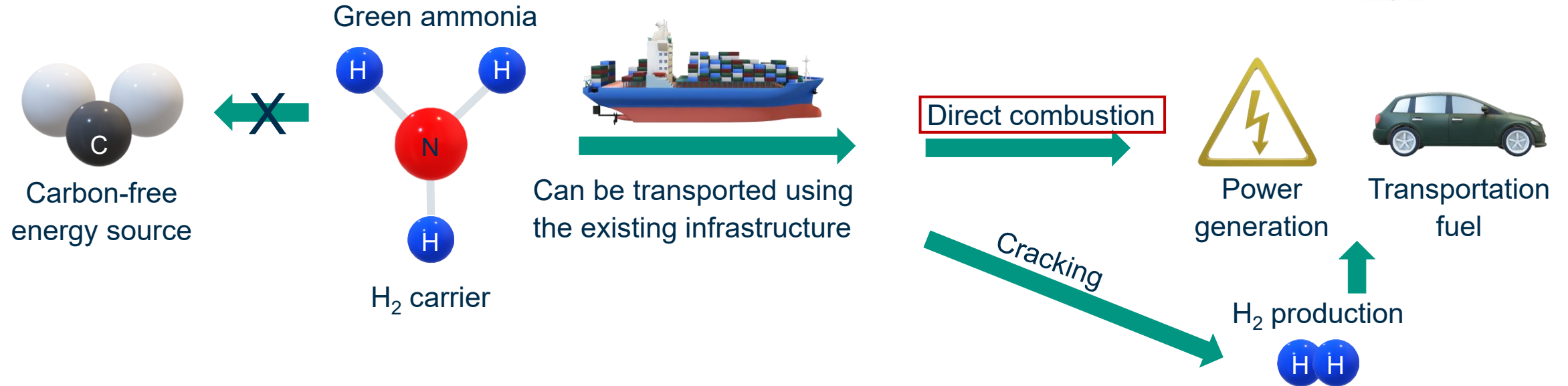
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Ammonia as an energy source



Challenges of NH₃ combustion

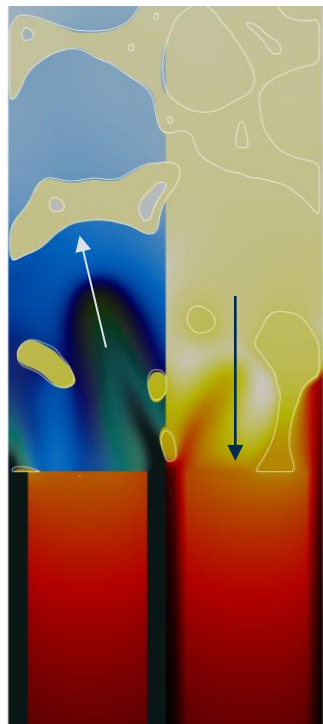
- High NO_x emissions at lean conditions
- NH₃ slip at rich conditions
- High toxicity
- Poor flame stability

Porous media combustion

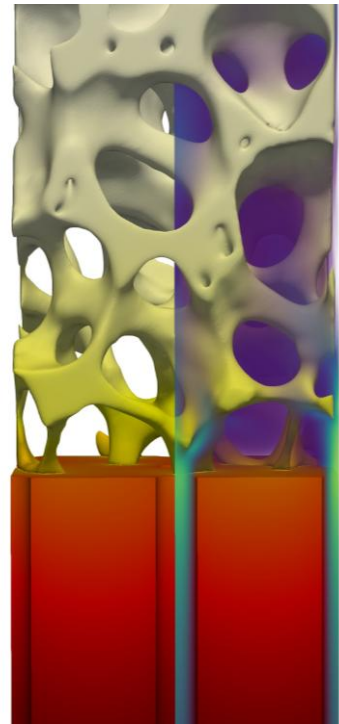
Improve combustion characteristics of ammonia^{1,2}

Direct pore-level simulations (DPLS)

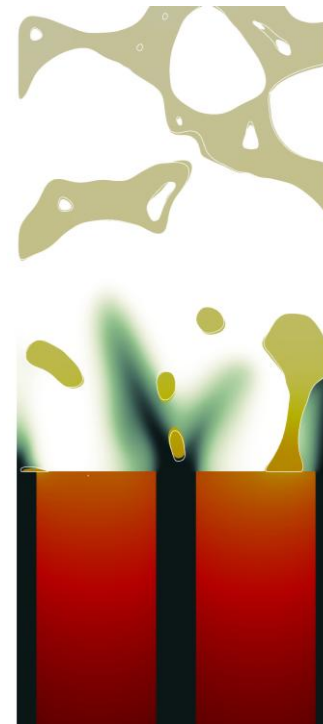
Simulation time: 2 mil. CPU-h
with 7200 CPUs



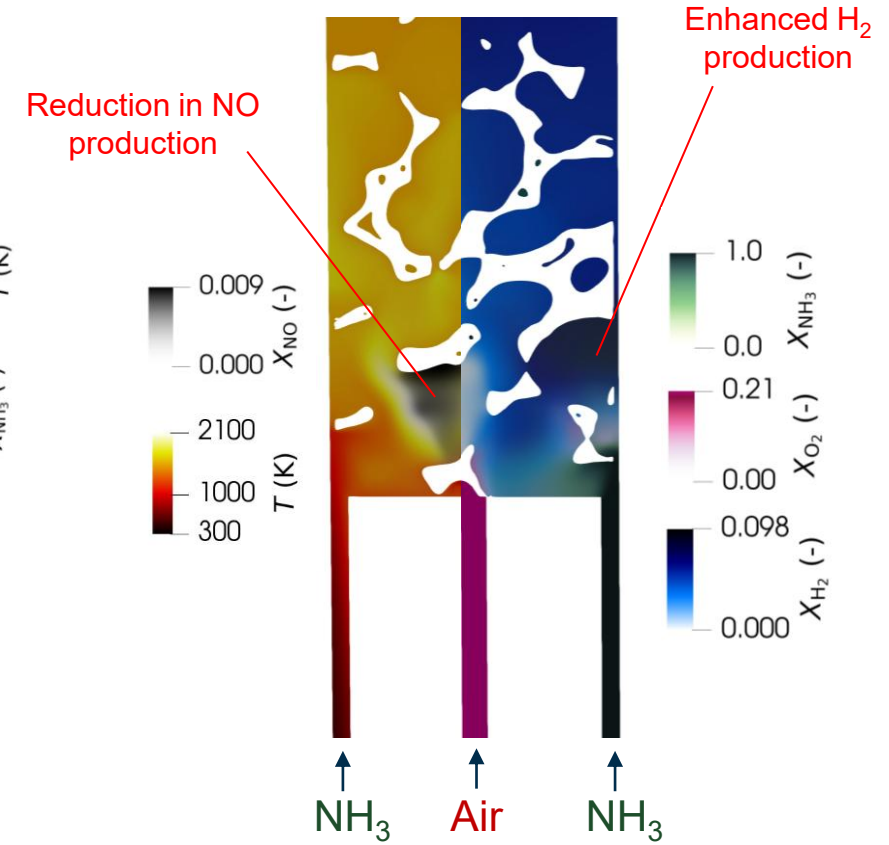
Induced heat
recirculation



Increased effective
burning velocity



Complete burnout of
NH₃



Non-premixed operation

1. Vignat et al., <https://doi.org/10.1016/j.proci.2022.07.054>
2. Kin et al., <https://doi.org/10.1080/00102202.2025.2464805>

Numerical modelling

Volume-averaged simulation (VAS)¹

The volume-averaged conservation equation of mass, momentum, species, and energy for reacting porous media flow are solved.

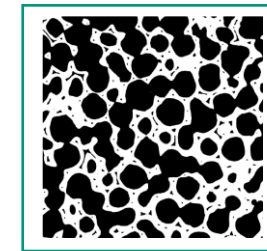
Energy conservation equations

$$\frac{\partial(\gamma\rho H_{tot})}{\partial t} + \nabla \cdot (\gamma\rho \vec{u} H_{tot}) = -\nabla \cdot (\gamma \vec{q}) + \gamma \frac{\partial p}{\partial t} - \gamma \sum_k (h_k^0 \dot{\omega}_k) - h_v(T - T_s)$$

$$\vec{q} = -\underbrace{(0.5|\vec{u}| \mathbf{d}_{disp} \rho)}_{\text{Dispersion}} \nabla h_s + \sum_k h_{s,k} \hat{j}_k + \frac{\lambda}{\eta c_p} \left(-\nabla h_s + \sum_k h_{s,k} \nabla Y_k \right) \quad \text{Gas phase}$$

$$(1 - \gamma) \rho_s c_s \beta \frac{\partial T_s}{\partial t} = \nabla \cdot (\lambda_{s,eff} \nabla T_s) + \nabla \cdot (\lambda_{rad} \nabla T_s) + h_v(T - T_s) \quad \text{Solid phase}$$

Material properties can be varied along the burner axis to simulate multi-layer porous burners.



SiSiC 15 PPI

Effective material properties

Mean pore diameter, d_p
Specific surface area, S_v
Porosity, γ

μ -CT
Scans

Tortuosity factor, η
Axial thermal conductivity factor, a
Extinction coefficient, κ

PUMA

$$h_v = Nu \frac{S_v^2 \mu}{4\gamma}$$

$$\lambda_{rad} = \frac{16\sigma T_s}{3\kappa}$$

$$\lambda_{eff} = a \left(\frac{T_s}{T_0} \right)^b$$

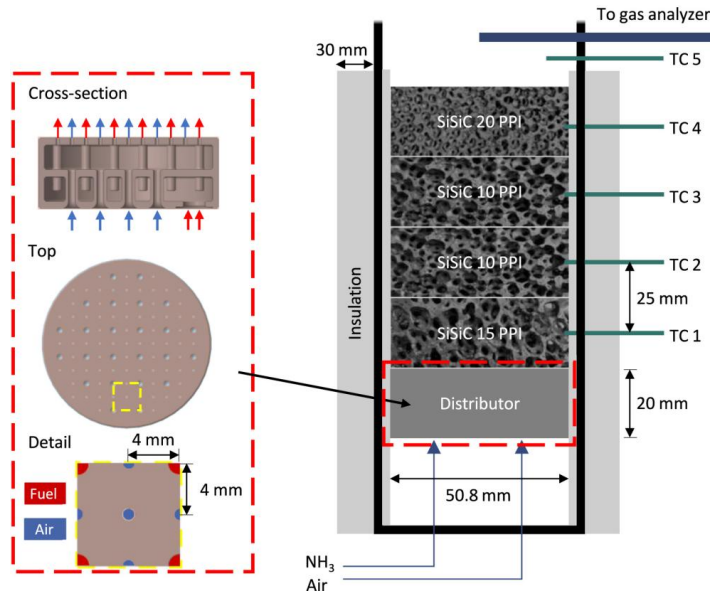
$$Nu = 3.7 Re^{0.38} Pr^{0.25} \quad \sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$$

$$T_0 = 293 \text{ K} \quad d_{disp} = f(d_p)$$

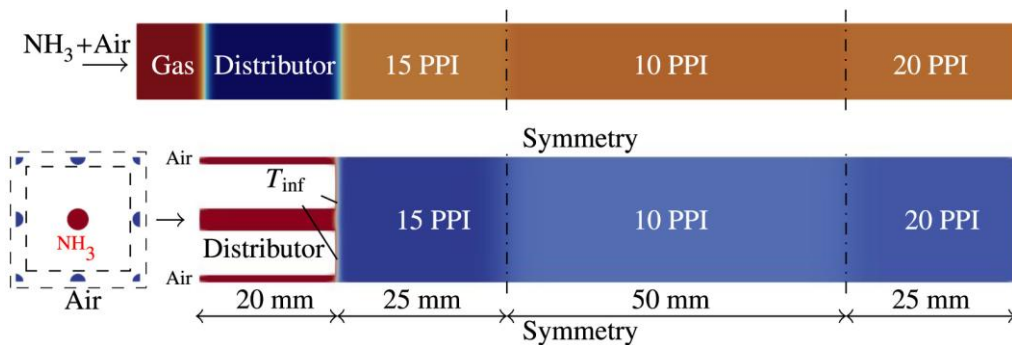
1. Puri et al., <https://doi.org/10.1016/j.proci.2025.105856>
2. PUMA: Ferguson et al., <https://doi.org/10.1016/j.softx.2021.100775>

Premixed vs. Non-premixed operation

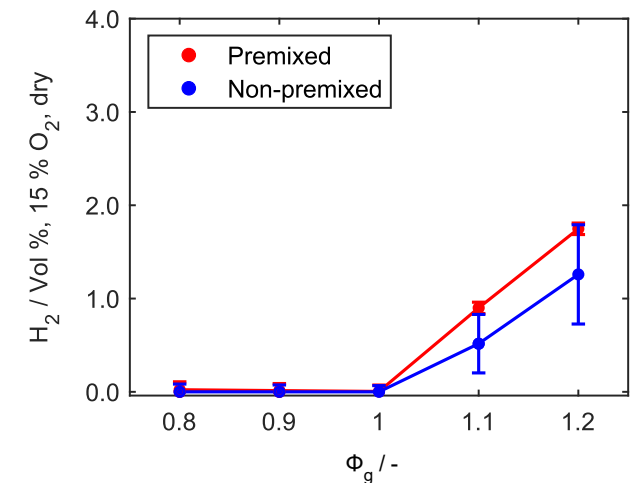
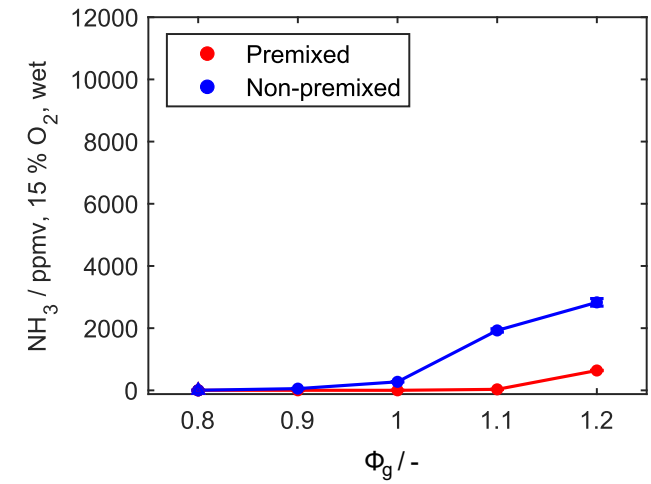
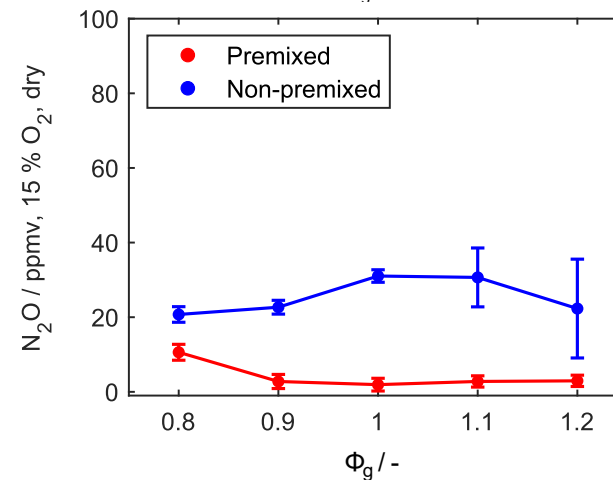
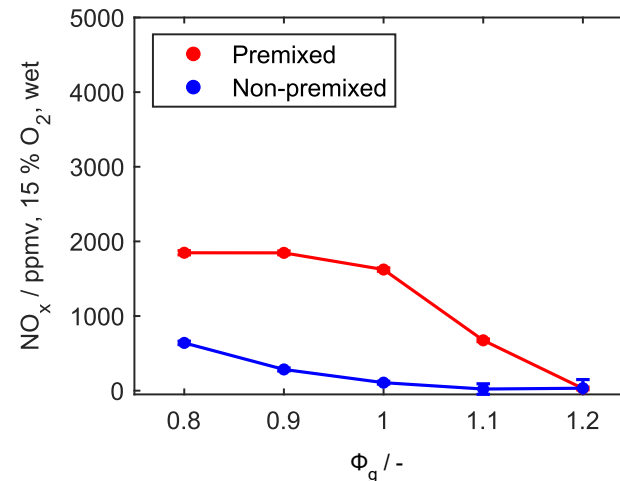
Experiment



Multi-layer porous burner

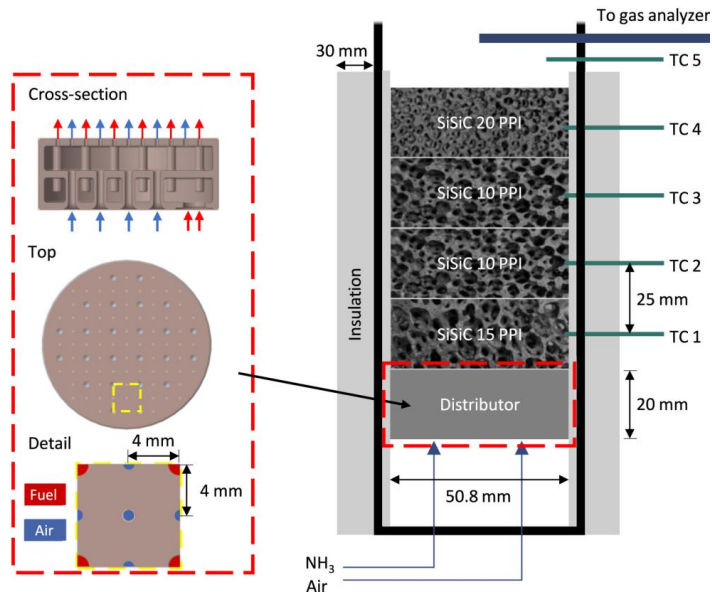


$P = 0.51 \text{ MWm}^{-2}$

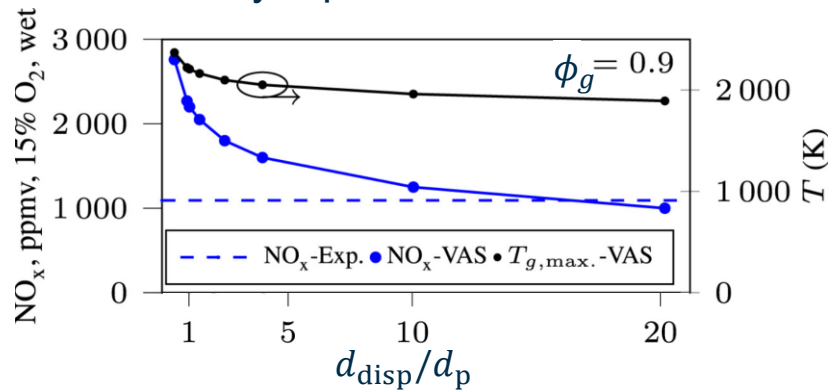


1. Kretzler et al., <https://doi.org/10.1016/j.jaecs.2026.100526>
2. Puri et al. <https://doi.org/10.1016/j.proci.2025.105856>

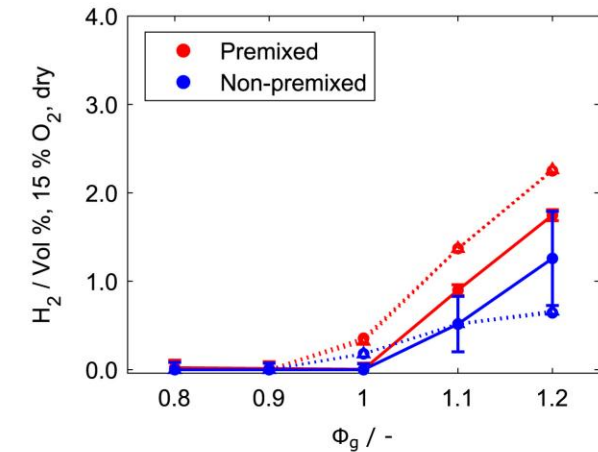
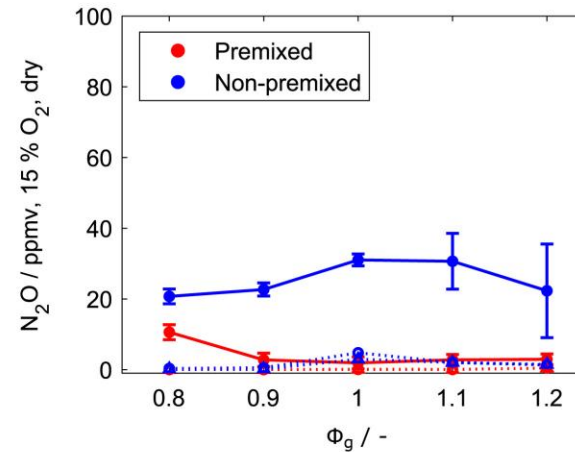
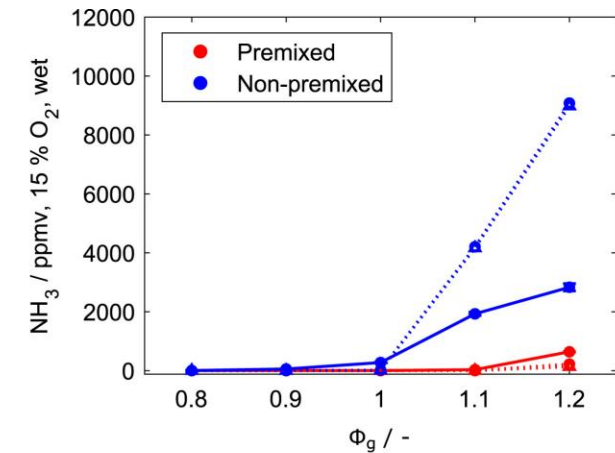
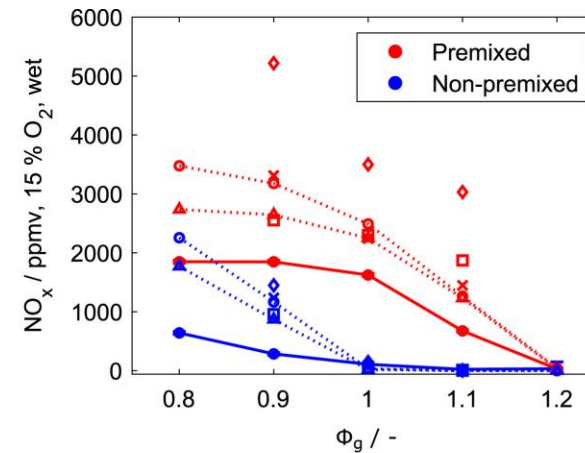
Premixed vs. Non-premixed operation



Multi-layer porous burner



Influence of the chosen dispersion length²



● Experimental data ●●● NUIG mechanism ●▲● Stagni mechanism × KAUST mechanism ◇ Konnov mechanism □ Shrestha mechanism

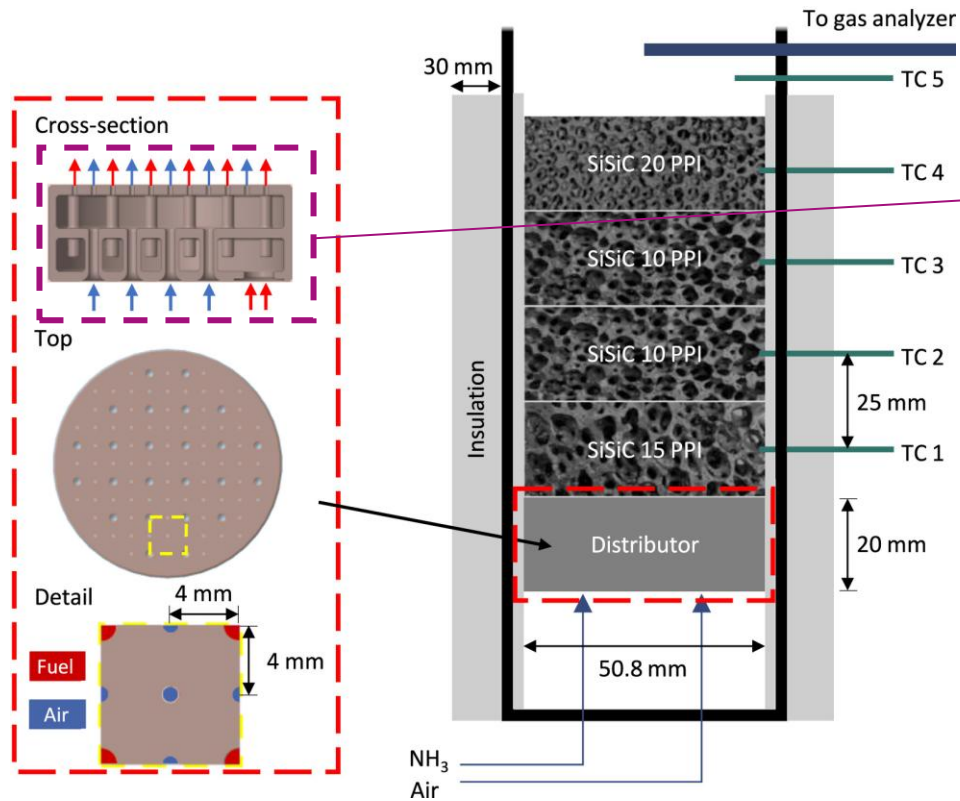
$P = 0.51 \text{ MWm}^{-2}$ $d_{disp} = 0.1d_p$

1. Kretzler et al., <https://doi.org/10.1016/j.jaecs.2026.100526>
2. Puri et al. <https://doi.org/10.1016/j.proci.2025.105856>

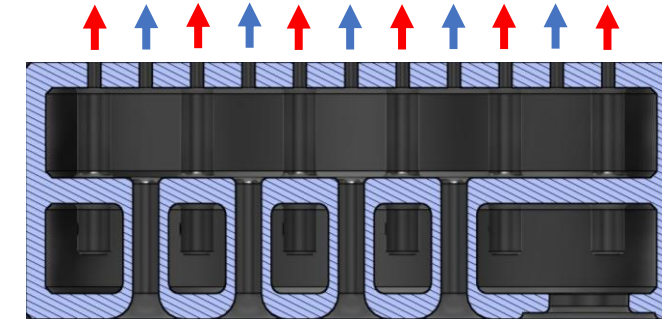
Premixed → **Non-premixed** → Reduced NO_x emissions

Is non-premixed combustion in porous media the optimal solution for ammonia?

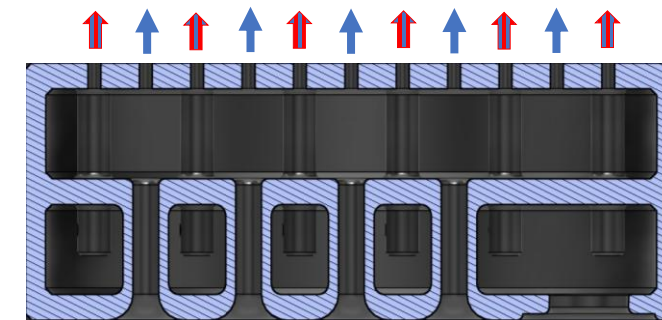
Partial premixing Concept



Multi-layer porous burner



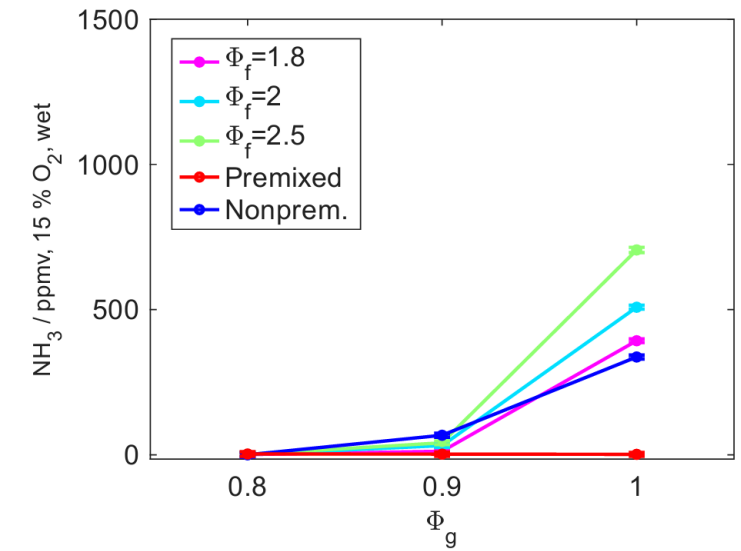
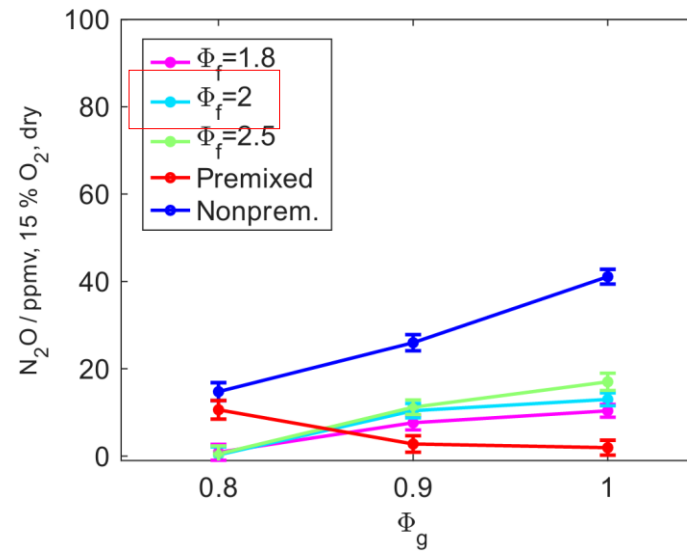
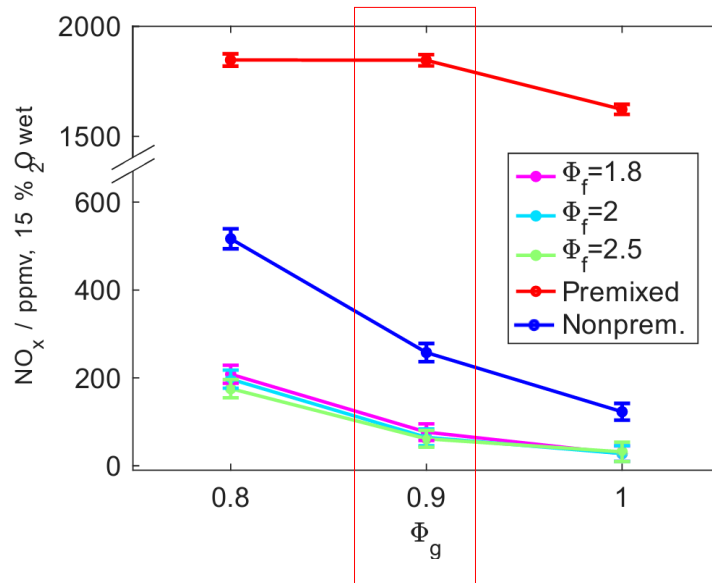
Non-premixed operation



Partially-premixed operation

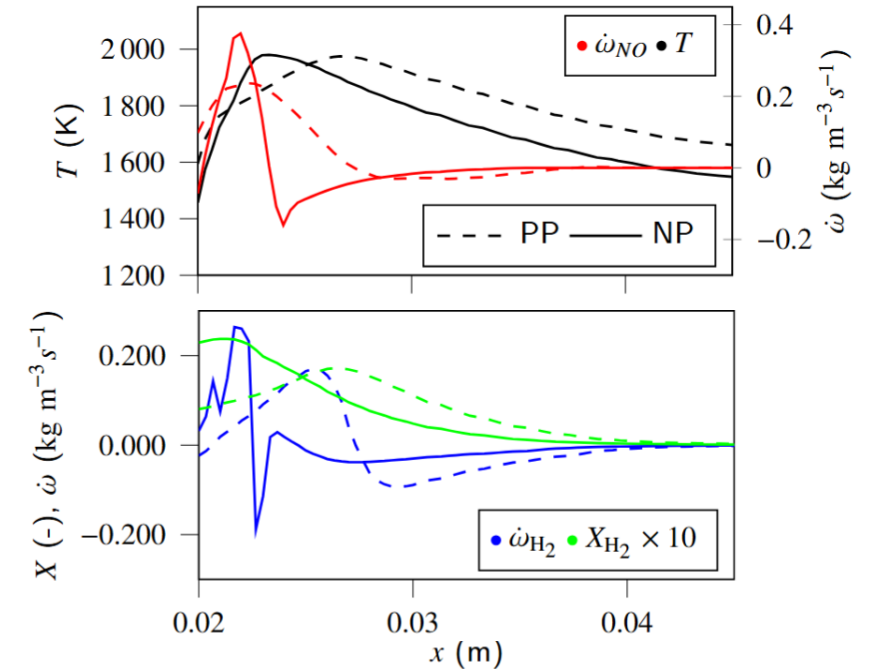
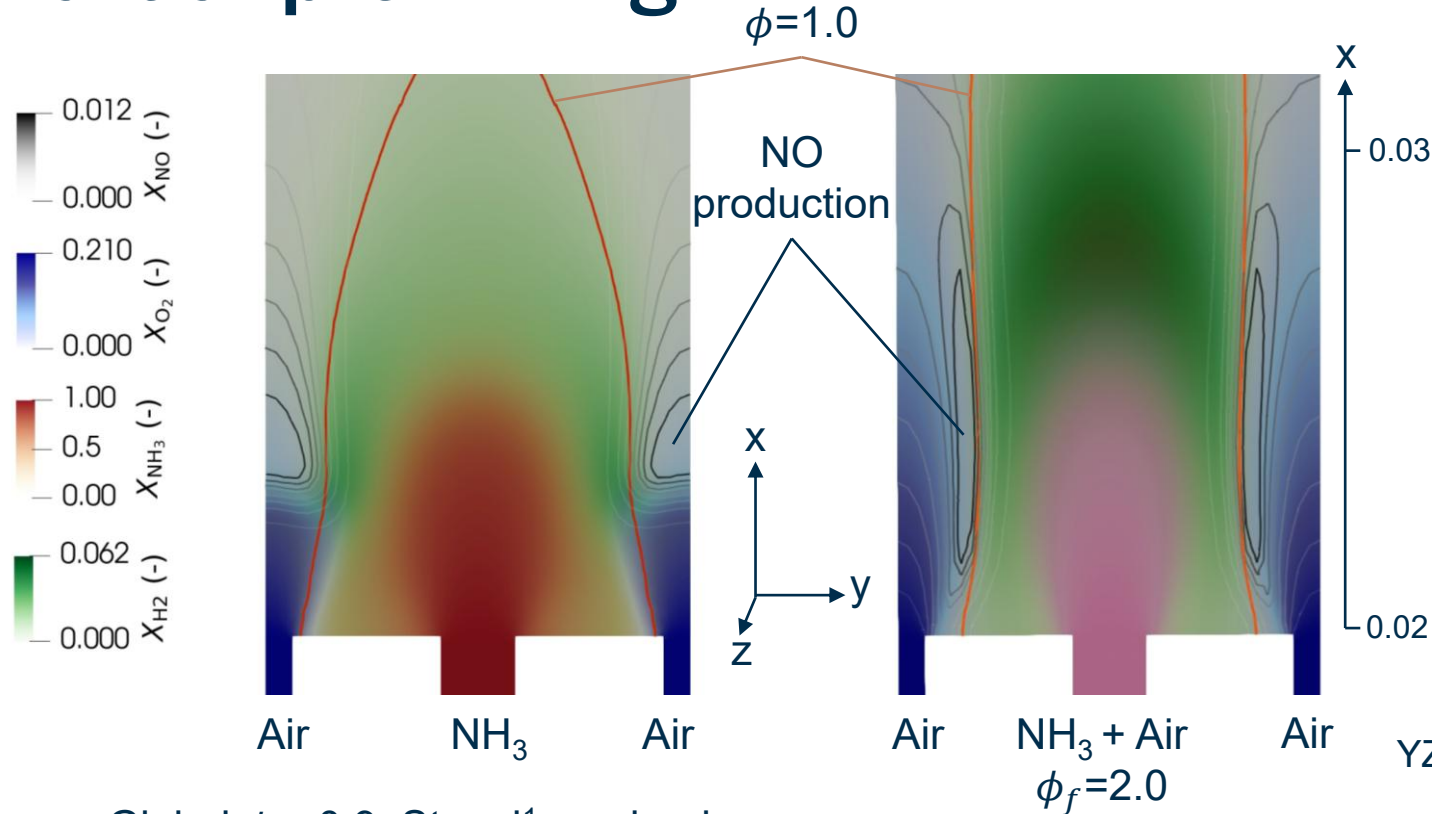
Partial premixing

Preliminary experimental results



Emissions decrease for the partially-premixed operation at the selected **lean conditions**.

Partial premixing



YZ-cross-section-averaged variation along the burner axis

($\dot{\omega}_{\text{NO}}$ is scaled by 0.2 for the non-premixed operation)

- Global $\phi_g = 0.9$; Stagni¹ mechanism

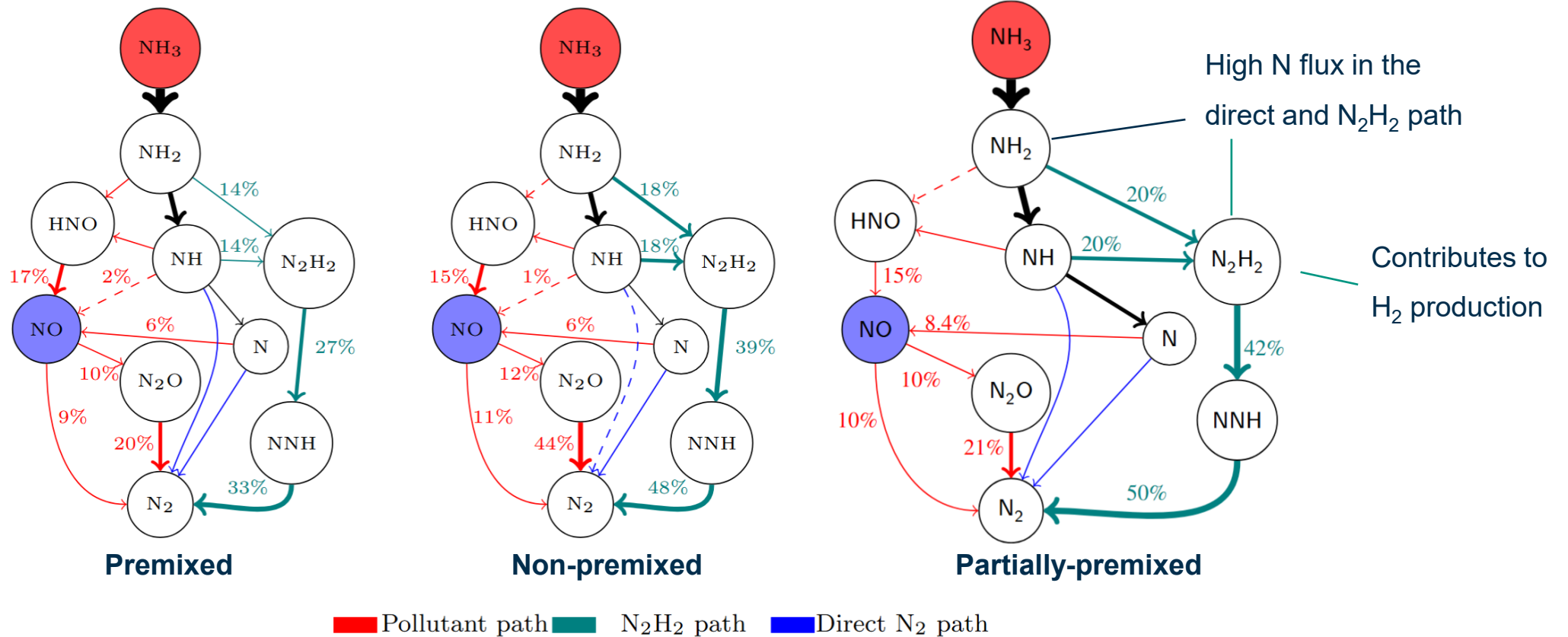
Operation	$\dot{\omega}_{\text{H}_2}$ (kg/m ³ /s) Net production	NO (ppmv, 15% O ₂ , wet)	NO ₂ (ppmv, 15% O ₂ , wet)	N ₂ O (ppmv, 15% O ₂ , dry)	H ₂ (%v)
Non-premixed	0.0194	863	6.41	0.191	1.93×10^{-5}
Partially-premixed	0.0279	626	5.27	0.0338	3.91×10^{-5}

1. Stagni et al., [doi:10.1039/c9re00429g](https://doi.org/10.1039/c9re00429g)

Partial premixing

Reaction path analysis of NO production

-->0 - 5% →5 - 15% →15 - 30% →30 - 70% →> 70%

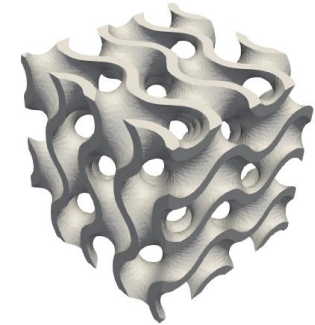


Conclusions

- Ammonia is considered to be a carbon-free fuel for the future energy infrastructure.
- Non-premixed combustion in porous media can improve the combustion characteristics of ammonia.
- As compared to the non-premixed operation, the partially-premixed operation leads to
 - Decrease in NO and N₂O emissions at selected lean conditions
 - Increase in H₂ production from NH₃ cracking
- Stronger direct and N₂H₂ paths assist in reduction of emissions.

Outlook

- Investigation of further operating points for the partially-premixed operation
- Validation with experimental results
- Optimisation and integration of gyroid-based distributors





Thank you!

Acknowledgements



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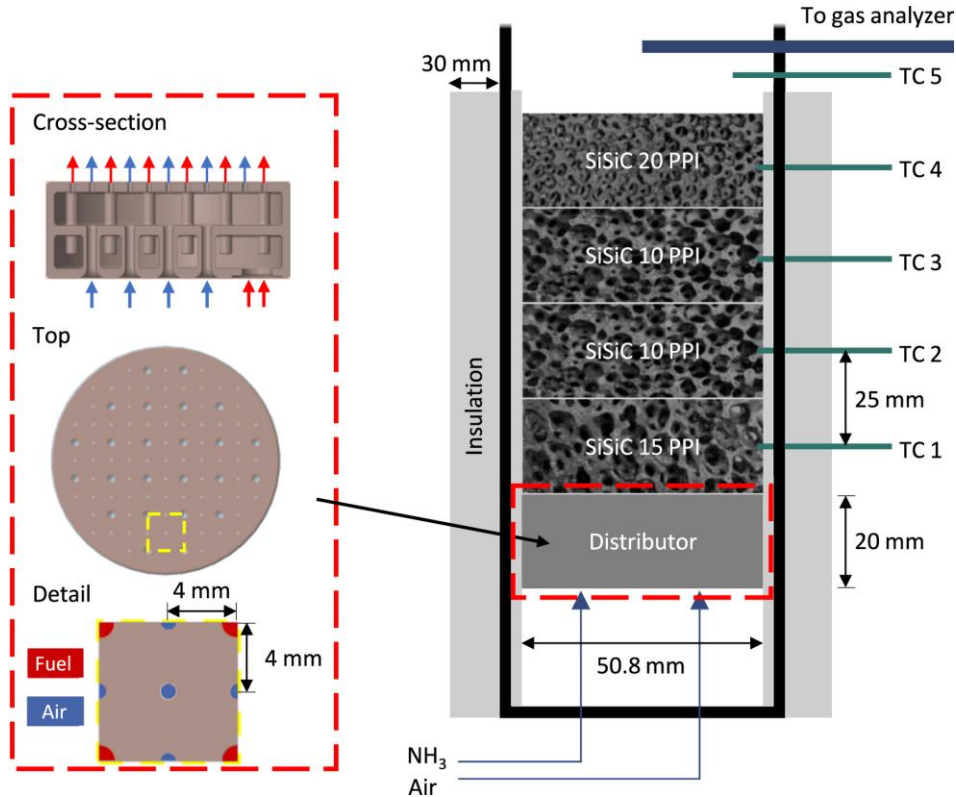
Christos G. Aneziris



SPP 2419 HyCAM
Hydrogen-based fuel combustion
using additive manufacturing

Premixed vs. Non-premixed operation

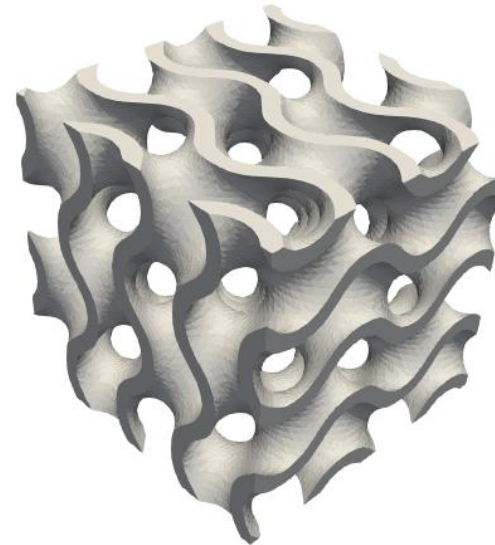
Geometry optimisation



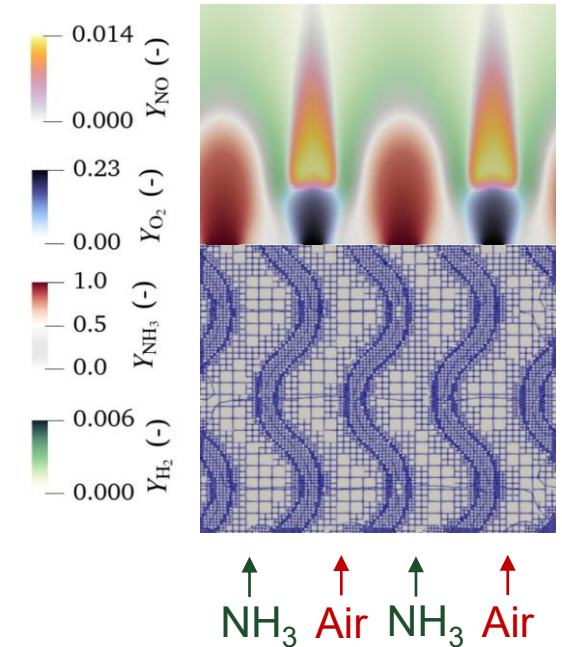
Multi-layer porous burner

Distributor optimisation using TPMS-Gyroid² (TUBAF)

$$U = \cos(2\pi wx)\sin(2\pi wy) + \cos(2\pi wy)\sin(2\pi wz) + \cos(2\pi wz)\sin(2\pi wx) \pm q$$



- Higher specific surface area
- Lower pressure loss along the flow direction



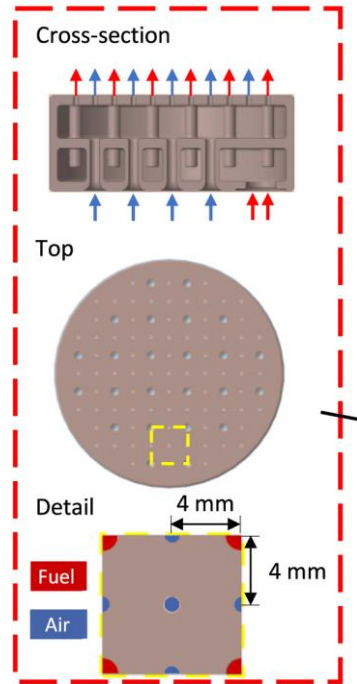
Non-premixed operation

- Kretzler et al., <https://doi.org/10.1016/j.jaecs.2026.100526>
- Sobhani et al., <https://doi.org/10.1016/j.proci.2018.05.155>

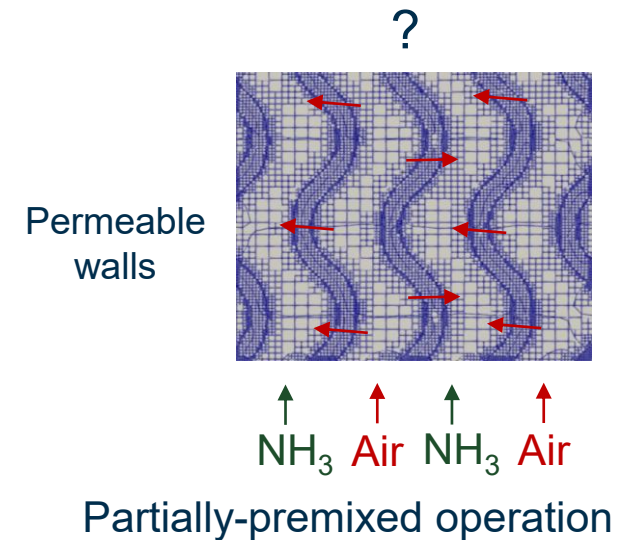
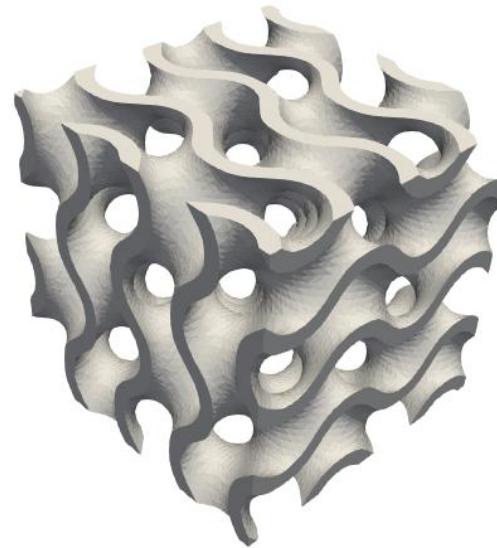
Premixed vs. Non-premixed operation

Distributor optimisation using TPMS-Gyroid² (TUBAF)

$$U = \cos(2\pi wx)\sin(2\pi wy) + \cos(2\pi wy)\sin(2\pi wz) \\ + \cos(2\pi wz)\sin(2\pi wx) \pm q$$



Distributor for the non-premixed operation



1. Kretzler et al., <https://doi.org/10.1016/j.jaecs.2026.100526>
2. Sobhani et al., <https://doi.org/10.1016/j.proci.2018.05.155>