Challenges of hydrogen combustion and its impact on emission regulations

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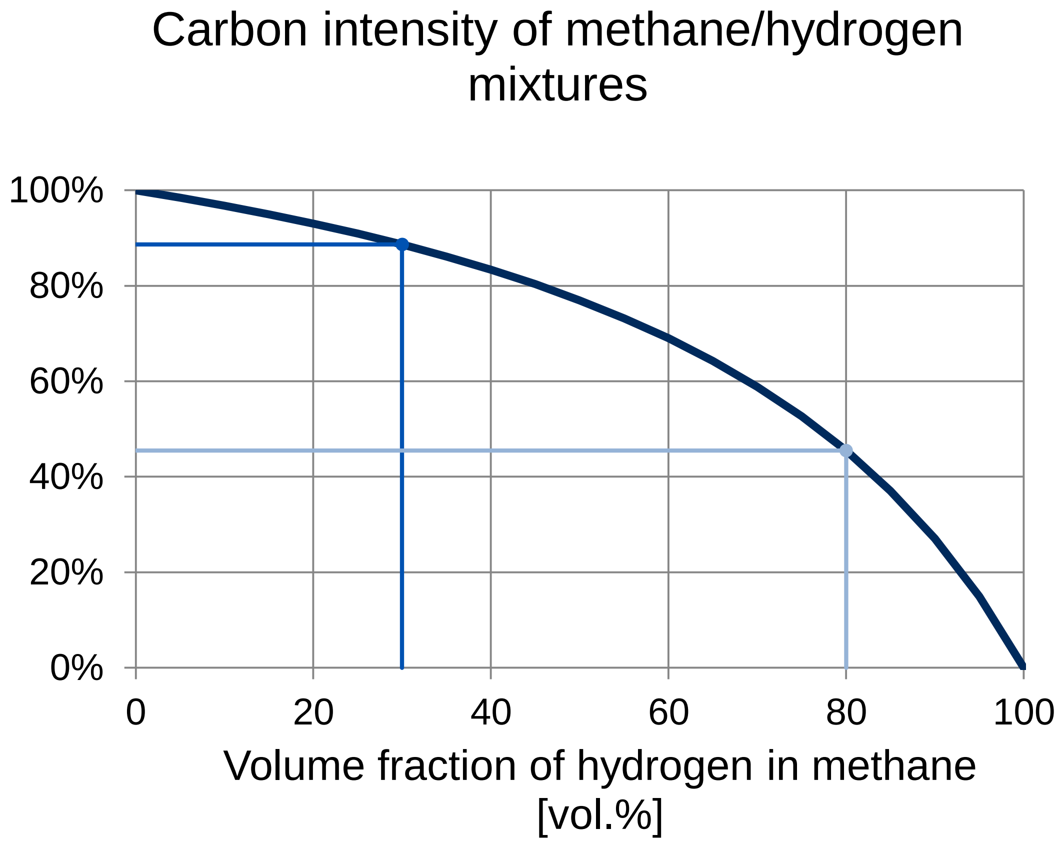
Hydrogen content vs. carbon intensity

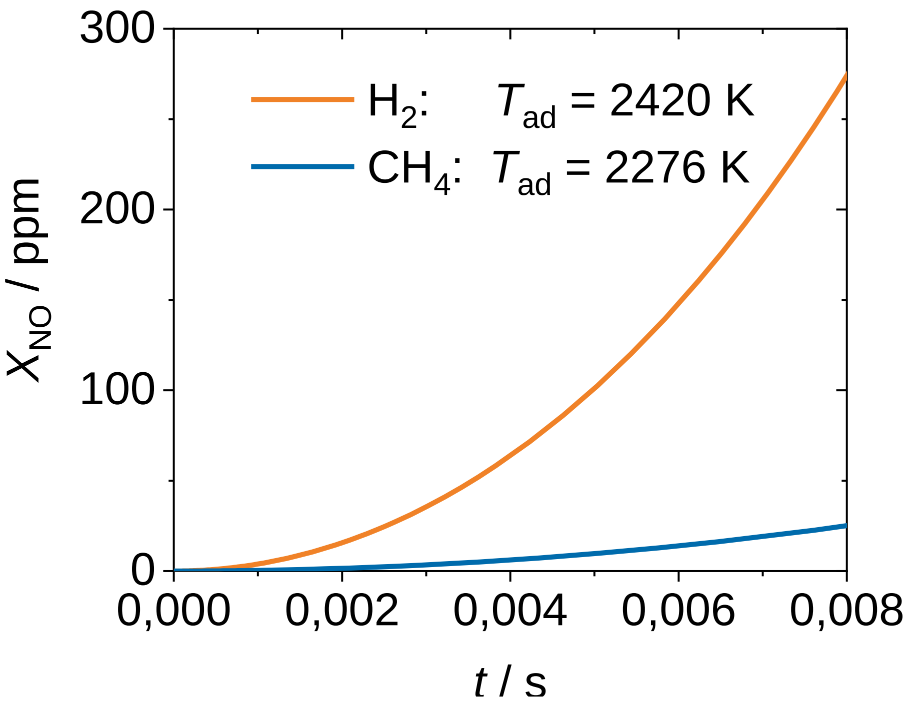
A motivation for 100% hydrogen

- High hydrogen content in fuel is inevitable to:
    - Reach a significant reduction in CO_2 emissions
    - Fulfill the European taxonomy regulation
    - Provide competitive technology for a future energy system



Hydrogen effects on NO_x formation

- Adiabatic flame temperature increases with hydrogen
- Temperature (and residence time) have a strong effect on thermal NO_x formation



$T_0 = 400\ \mathrm{K}, p = 1\ \mathrm{atm}, \lambda = 1$

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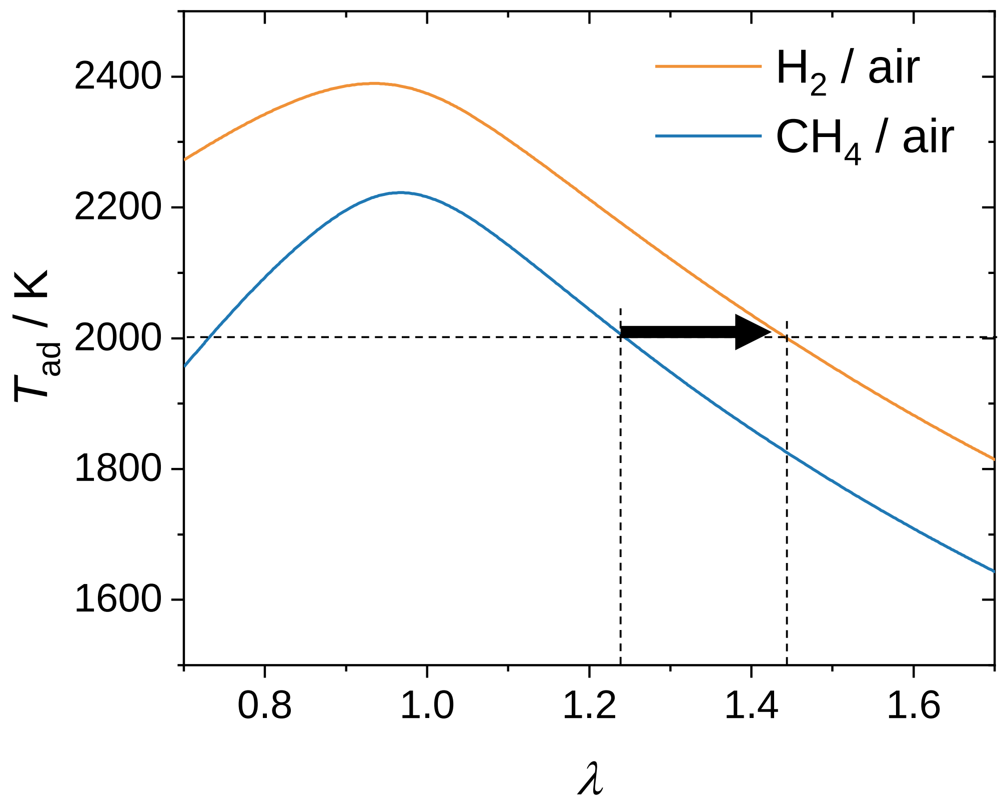

$T_0 = 273\ \mathrm{K}, p = 1\ \mathrm{atm}$

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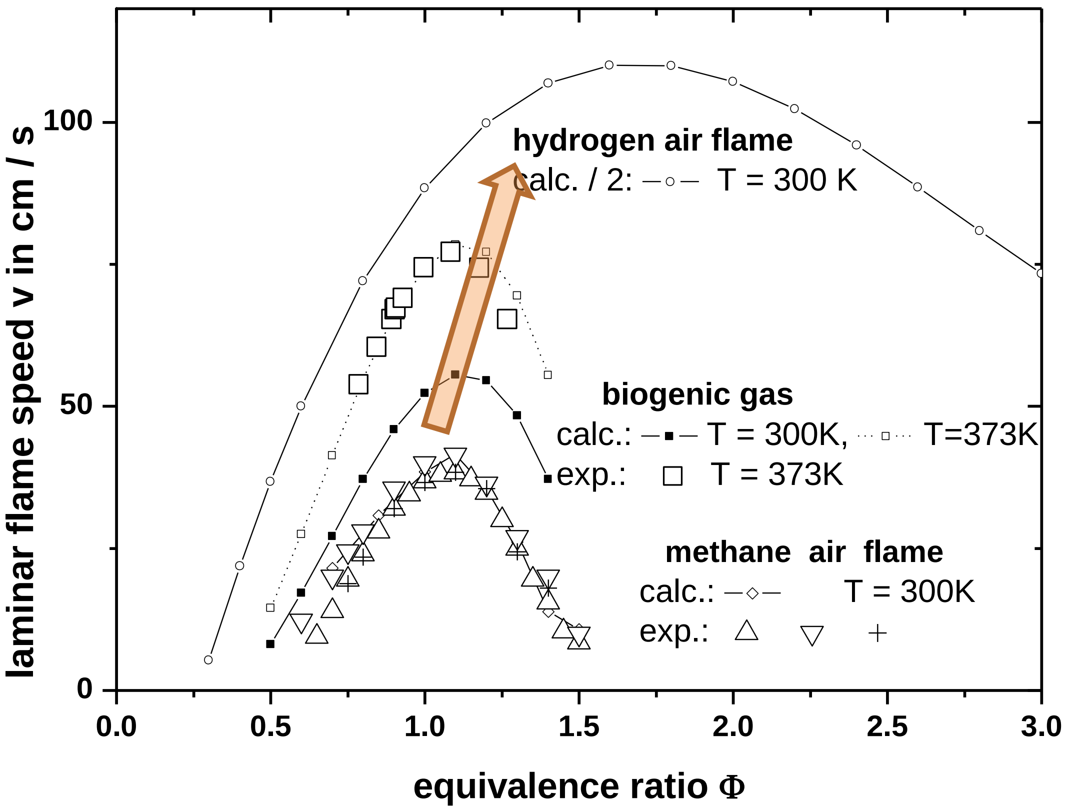

[1]

[1] Herzler et.al., Alternative Fuels based on biomass: an investigation on combustion properties of product gases, J. Eng. Gas Turbines Power 135(3), 031401–01 - 031401–09, doi 10.1115/1.4007817 (2013)

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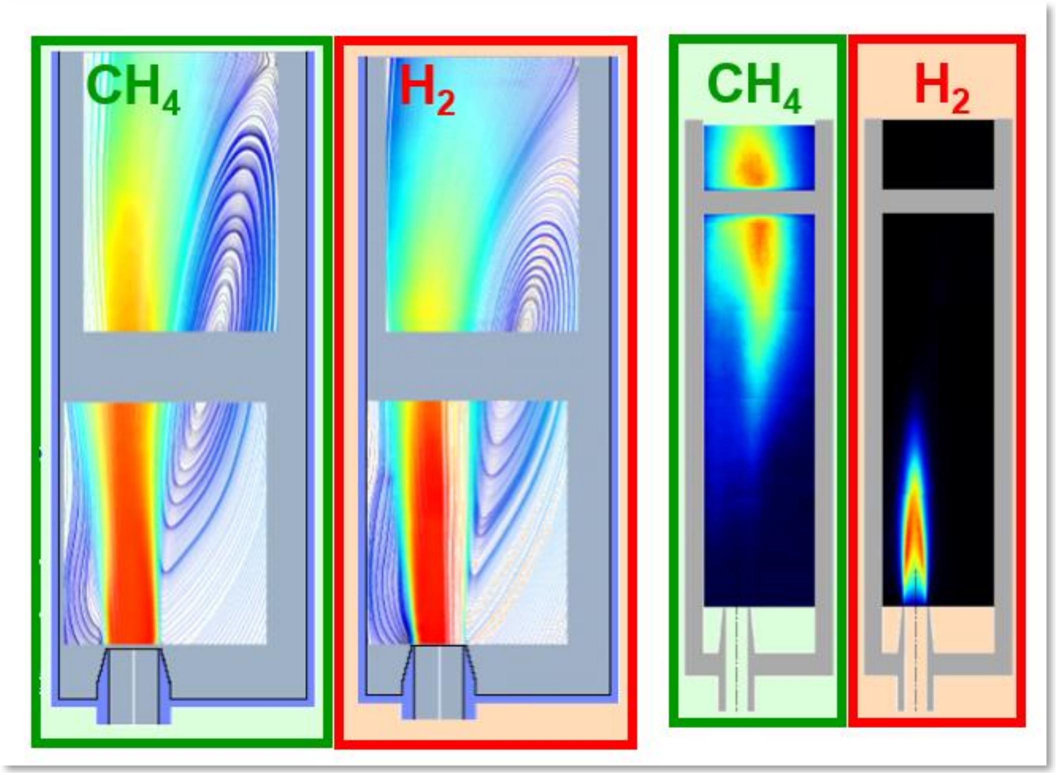

[2] [3]

[2] Lammel et al., Investigation of Flame Stabilization in a High-Pressure Multi-Jet Combustor by Laser Measurement Techniques, Proc. ASME Turbo Expo 2014, GT2014-26376
[3] Lammel et al., Experimental Analysis of Confined Jet Flames by Laser Measurement Techniques , J. Eng. Gas Turbines Power 134 (2012) 041506

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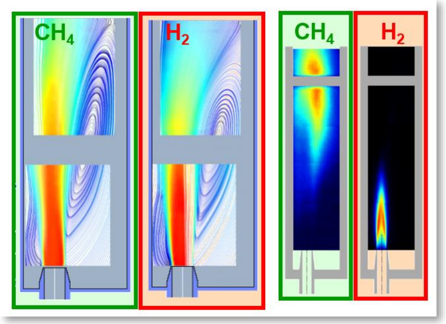

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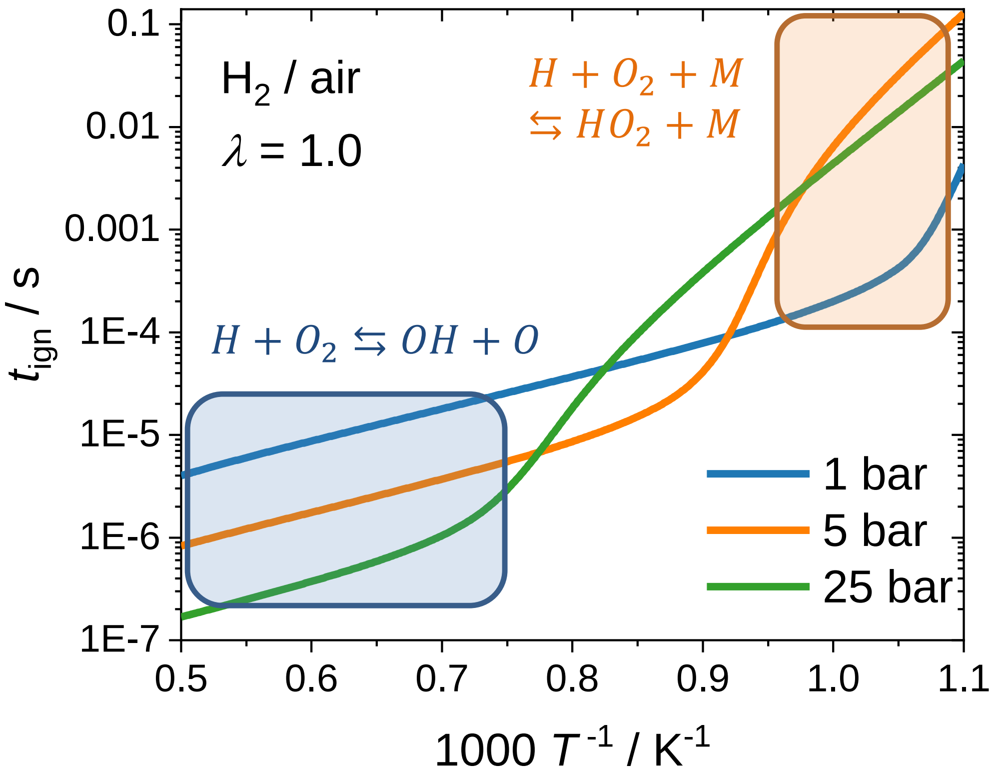
  - pressure effect of ignition delay time

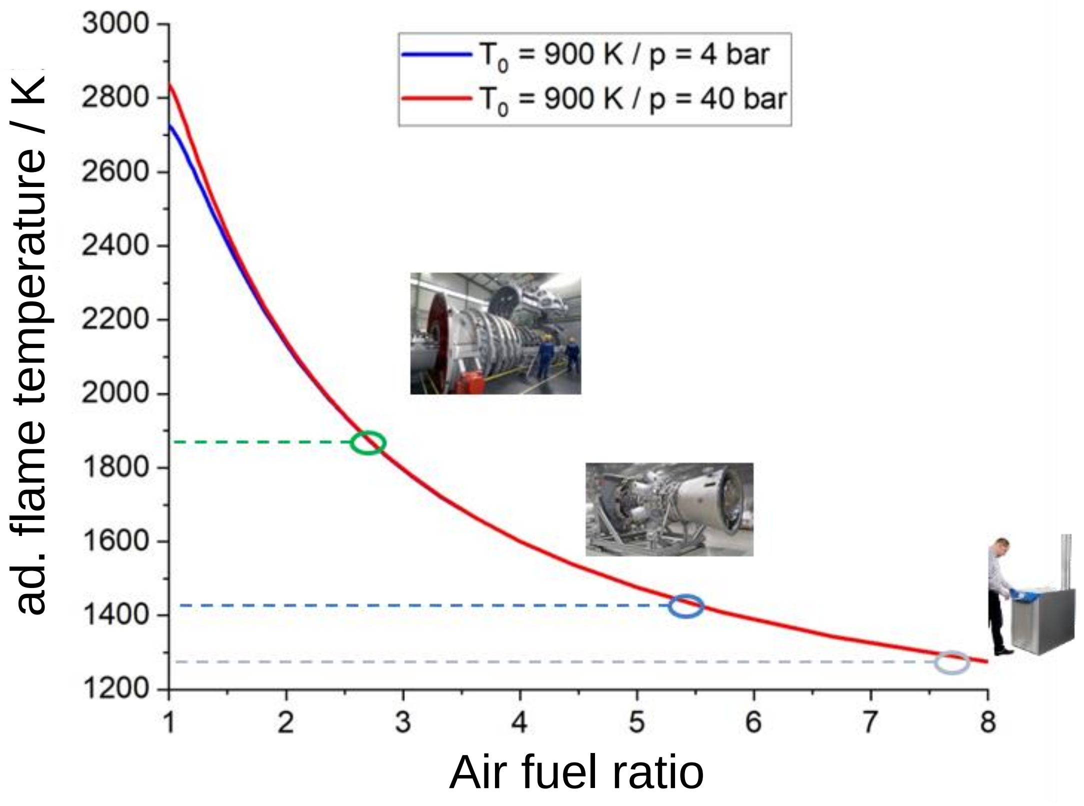
  has to be considered in combustion systems to prevent flash back



www.dlr.de/VT/mechanisms

Different challenges depending on gas turbine size

- Efficiency of heavy duty gas turbines depends on high combustion temperature → reduced residence time could be an option for low NO_x emissions
- Industrial gas turbines could benefit from lean premixed combustion systems with high air / fuel ratios
- Very small gas turbines (recuperated cycles) face the challenge of combustor inlet temperatures higher than self ignition temperature of hydrogen / air mixtures



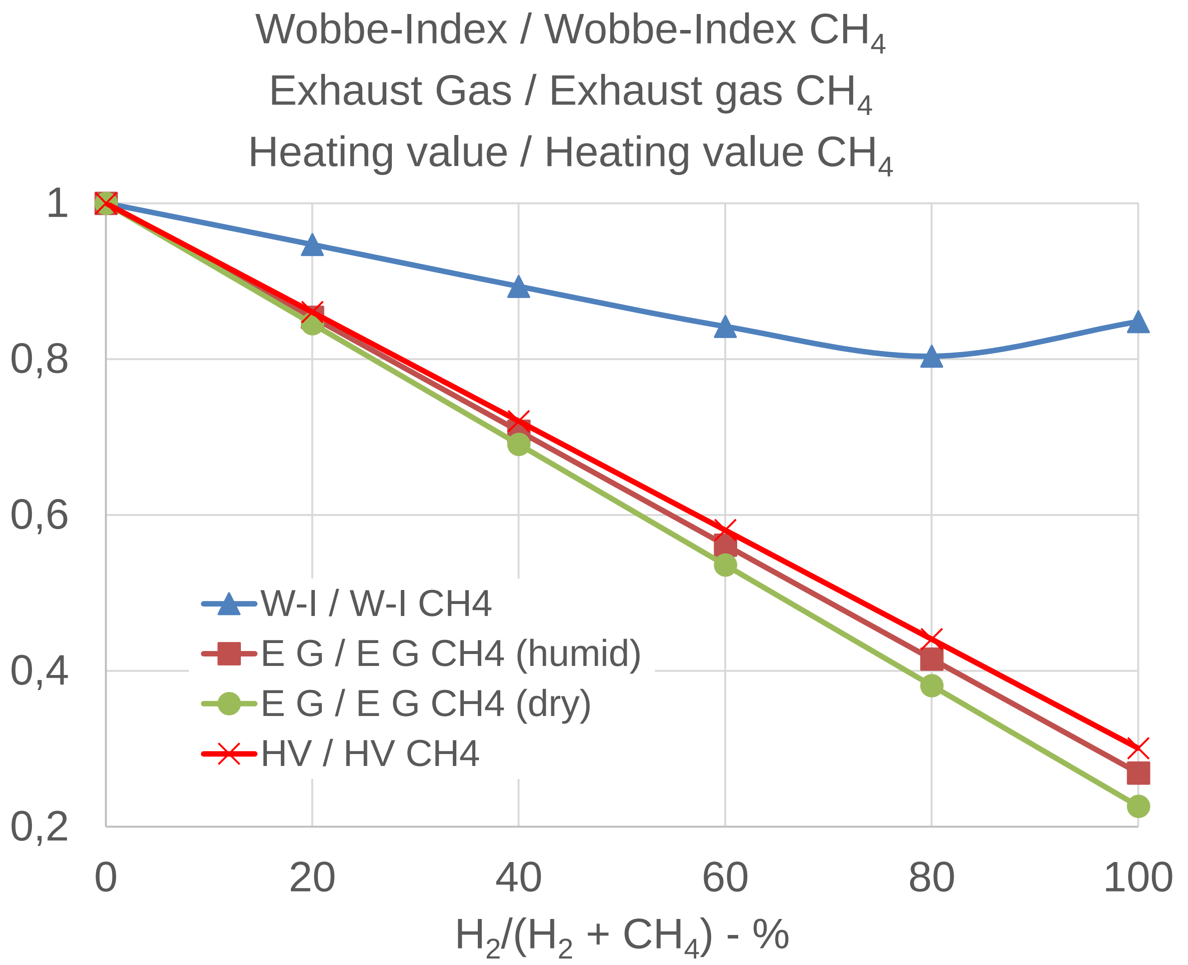
Aspects of hydrogen combustion in respect to emission regulations

- Strong dependence on
  - Heating value
  - Air and exhaust gas volume flow
  - Exhaust gas composition

- Exhaust gas, standard reference conditions:

$T = 273{,}15\ \mathrm{K},\ \ p = 101{,}3\ \mathrm{kPa}$, **dry, @15 Vol.% O_2**

$$NO_X = \left[x_{NO} \,/\, x_{NO_2}\right]_{\mathrm{dry,\,ppm}} * \rho * \frac{(0{,}209 - 0{,}15)}{(0{,}209 - x_{O_2})} \ \ / \ \frac{\mathrm{mg}}{\mathrm{Nm^3}}$$



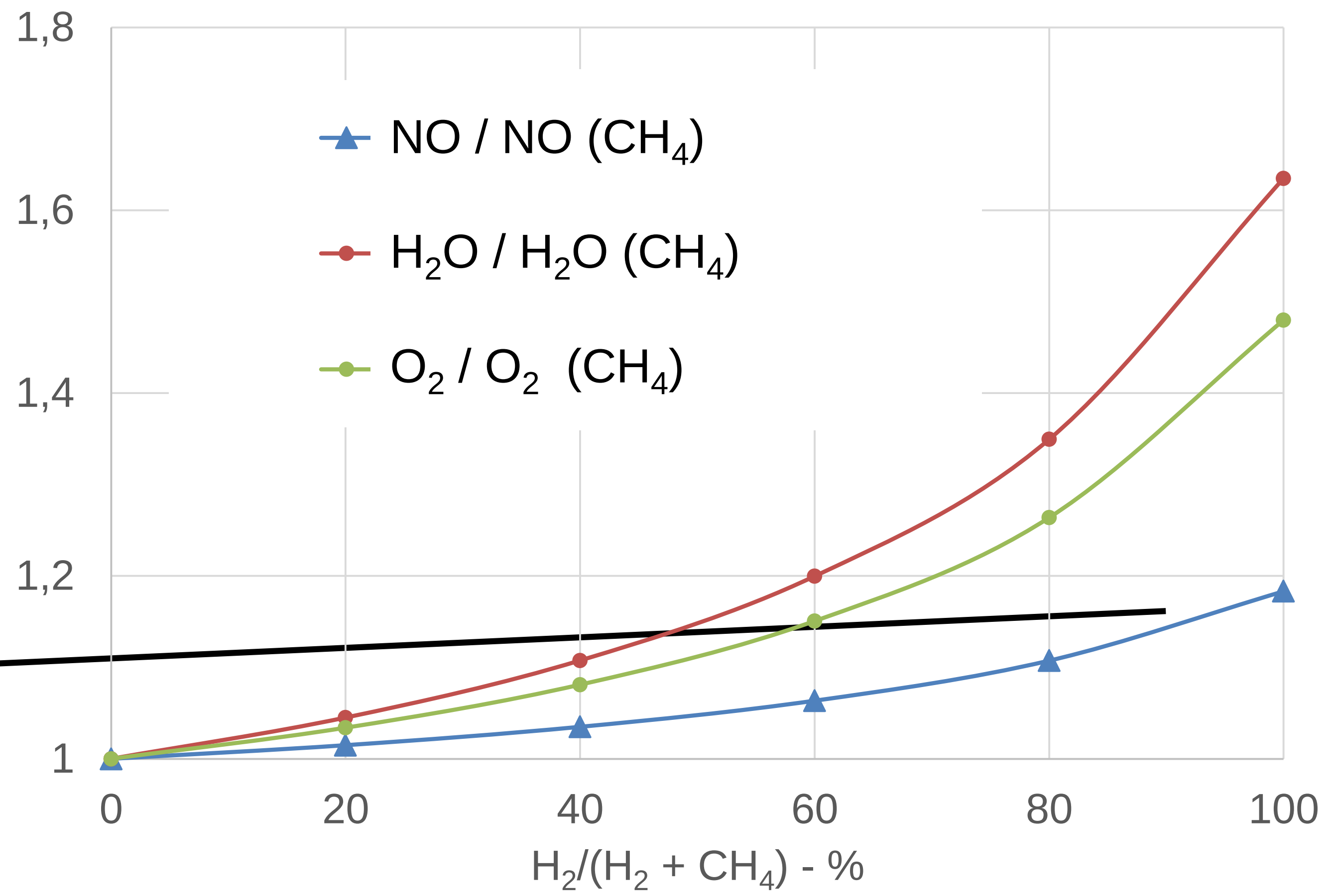
$\lambda = 1{,}24; T = 273\ \mathrm{K}, p = 101{,}3\ \mathrm{kPa}$

Calculation of NOx emission - normalized by current regulations
Example

Thermodynamic equilibrium:

- $T_{ad} = 2000\ \mathrm{K} = \mathrm{const.}$
- $p = 101{,}3\ \mathrm{kPa},\ \ T_0 = 298\ \mathrm{K}$
- $\lambda\,(CH_4) = \mathbf{1,24} \rightarrow \lambda\,(H_2) = \mathbf{1,44}$
- $P_{th}\,(CH_4; H_2) \approx 2{,}75\ {}^{\mathrm{MJ}}/_{\mathrm{Nm^3\,(exhaust\ gas)}}$

- NO increase due to differences in thermodynamic equilibrium



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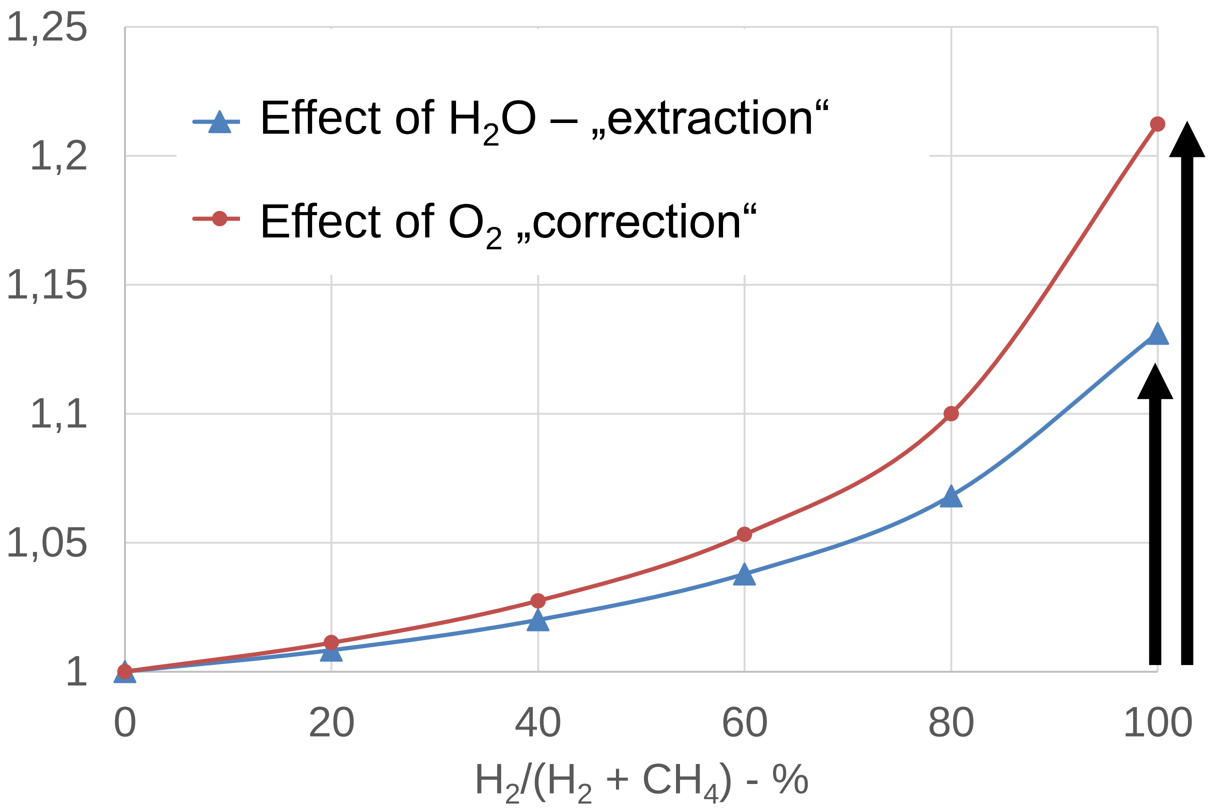


→ Influence of water

→ Influence of O_2 correction

$$NO_X = \left[x_{NO} \,/\, x_{NO_2}\right]_{\text{wet, ppm}} * \rho * \frac{1}{(1-x_{H_2O})} * \frac{(0{,}209-0{,}15)}{(0{,}209-x_{O_2})} \;/\; ^{\text{mg}}/_{\text{Nm}^3}$$

Calculation of NOx emission – different normalization approach (mg/kWh)

- Exhaust gas, standard reference conditions

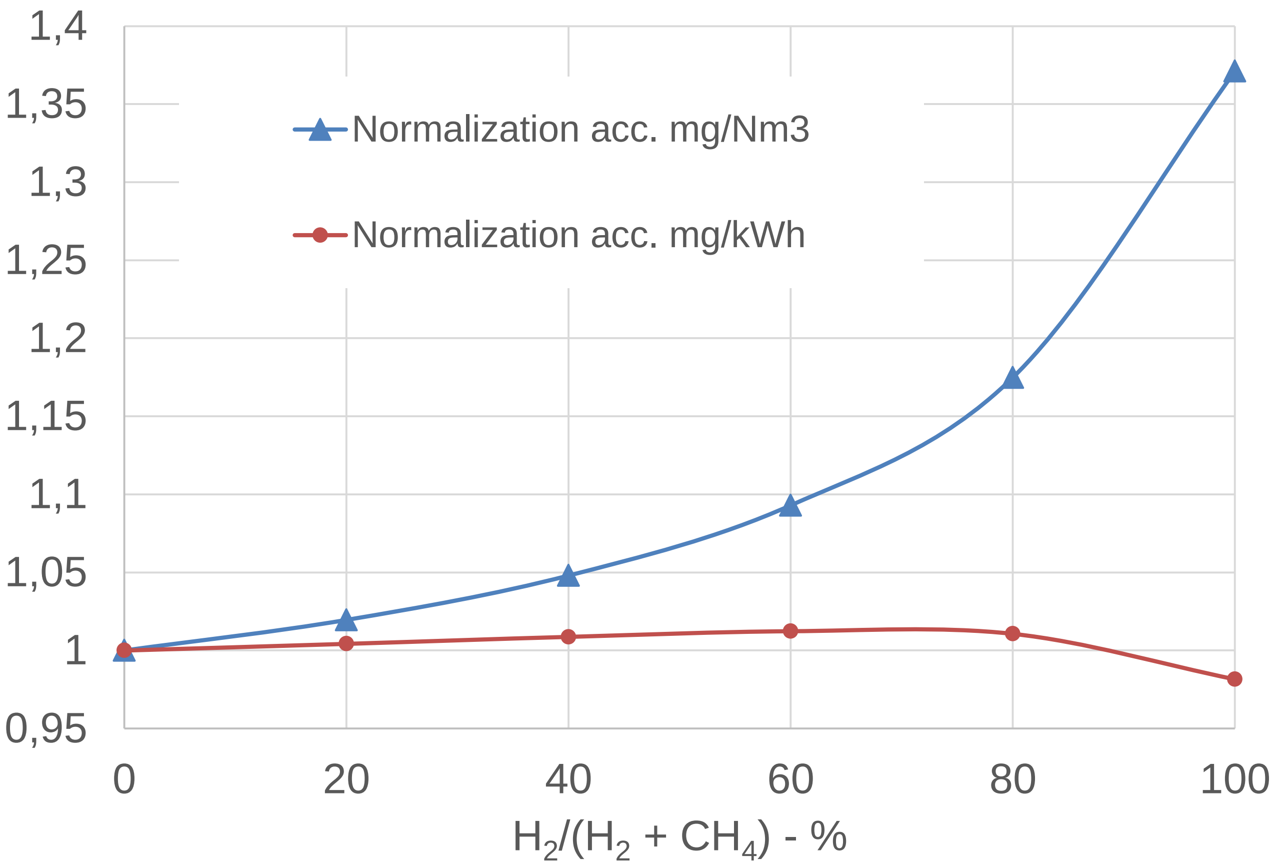
  ($T = 273{,}15\ \mathrm{K}, p = 101{,}3\ \mathrm{kPa}$), dry

$$NO_X = \left[x_{NO_2,\,\mathrm{dry}\,/\mathrm{ppm}}\right] * \rho * \frac{0{,}209}{\left(0{,}209 - x_{O_2}\right)} * \frac{q_{\mathrm{V,EG,dry,sto}}}{LHV} \quad / \frac{\mathrm{mg}}{\mathrm{kWh}}$$

- $q_{\mathrm{V,EG,dry,sto}}$ = stochiometric exhaust gas volume, dry - Nm^3/Nm^3
- LHV = Lower heating value - kWh/Nm^3
- Advantage: calculation of amount of NOx over time with known energy consumption
- used e.g. in EN 676:2020 (forced draught burners), 1. BImSchV (Germany), 813/2013 (ErP – Lot 1) (EU)

Calculation of NOx emission – comparison of normalization approaches

- Normalization in mg/kWh is the preferred method to account for the differences in the combustion of various gaseous fuels



Conclusions

- Hydrogen combustion increases adiabatic flame temperature and thus the risk of higher NOx emissions, but also decreases exhaust gas flow and change exhaust gas composition
- Current emission regulations (normalization) and measures do not account for the differences in natural gas and hydrogen combustion

→ Therefore it would be useful

  - to either keep current normalization (mg/Nm^3) and declare hydrogen as “further / other gases” with own emission limits
  - **or to use a normalization method (mg/kWh) using a quotient of the stochiometric dry exhaust gas volume and the lower heating value of the gaseous fuel**