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# Investigation of NO<sub>x</sub> and CO Formation at Ultra-Wet Conditions

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Motivation: Humid Gas Turbine Cycle



- In humid gas turbines, water or steam is injected into the cycle
- Efficiency increase:
  - Use of exhaust heat to generate steam
  - Improved cooling
- Reduced NO<sub>x</sub> emissions:
  - Lower flame temperature
  - Influence on chemical reactions
- Clean combustion of syngas and hydrogen
- Combustion at ultra-wet conditions allows for
  - Further increased efficiency up to 55-60% in single cycle application
  - CO<sub>2</sub>-sequestration: near-stoichiometric combustion leads to high concentration of CO<sub>2</sub> after condensation of the steam





SG: Heat Recovery Steam Generator





- Initial assessment of atmospheric combustion at ultra-wet conditions
- Development of a modeling tool for reaction kinetics
- Influence of steam on
  - Flame shape
  - Combustion process
  - Emissions formation





- Motivation and Background
- Experimental Setup and Results
- Design of Reactor Network and Validation
- Results of Network Model
- Conclusions



# Experimental setup:

#### Generic combustor







## OH\* Chemiluminescence:

Steam increases region of heat release





Dry flame

Flame with 20% steam

Flame with 30% steam

T<sub>ad</sub> = 1850 K



## Flame Temperature:

Flame not significantly longer







OH Radical Concentration:



















Measured CO,  $T_{in}$  = 645 K

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# Design of Reactor Network:



- Network layout
- Flame modeled by perfectly stirred reactor (PSR)
- Post flame zone modeled with a plug flow reactor (series of 20 PSRs)
- Heat loss:
  - Radiation (gray gas model and optical thin model)
  - Convective heat transfer based on measured cooling water temperature
- Reaction mechanisms:
  - GRI-Mech 3.0
  - Konnov "Reaction Mechanism for the Combustion of Small Hydrocarbons", rev 05
- Investigated operating conditions:
  - Two different fuel concentrations:  $X_{CH4}$  = 5.4% and  $X_{CH4}$  = 6.8% ( $\Phi$  =0.5...0.9)
  - Three flame temperatures:  $T_{flame}$  = 1670K, 1829K, 1970K









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## OH Radical Concentration:

Model predictions agree with experiments







## Results of Network Model:

Trends of experimental results well predicted





#### Measured and predicted emissions (Konnov)





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# Results of Network Model:

Influence of steam depends on dilution level





- CO formation CO + OH -> H + CO2 can be both increased and decreased at ultra-wet conditions
- NOx formation more affected by change in other species
  Spe

Species concentrations in flame reactor (GRI)

→ X<sub>CH4</sub> = 5.4%, T<sub>flame</sub> = 1673K

→ X<sub>CH4</sub> = 6.8%, T<sub>flame</sub> = 1673K

→  $X_{CH4} = 5.4\%$ ,  $T_{flame} = 1973K$ →  $X_{CH4} = 6.8\%$ ,  $T_{flame} = 1973K$ 



#### Results of Network Model: Prediction of very high CH concentrations





Species concentrations in flame reactor (GRI)



### Results of Network Model: Increase in prompt NO<sub>x</sub>



NOx pathways at dry conditions



#### NOx pathways at wet conditions



Calculated share of  $NO_x$  formation pathways





Experiments:

- Stable flame up to a degree of humidity of  $\Omega = 35\%$  for natural gas
- NO<sub>x</sub> emissions are significantly reduced
- CO is not noticeably affected by the steam (at atmospheric conditions) Investigation of chemistry:
- Developed model predicts the experimental results (NOx, CO, OH) well
- Influence of steam depends strongly on the degree of dilution
- Thermal NOx significantly reduced also at high temperatures
- Prompt NOx formation is predicted to increase with steam content, and might be over-predicted by the reaction mechanisms





#### Thank you for your attention.

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