

Numerical and Experimental Study of Hydrogen Combustion at High Pressures

IEA TLM Meeting

Heidelberg 13th-16th August 2006

Subtask 3.1 C

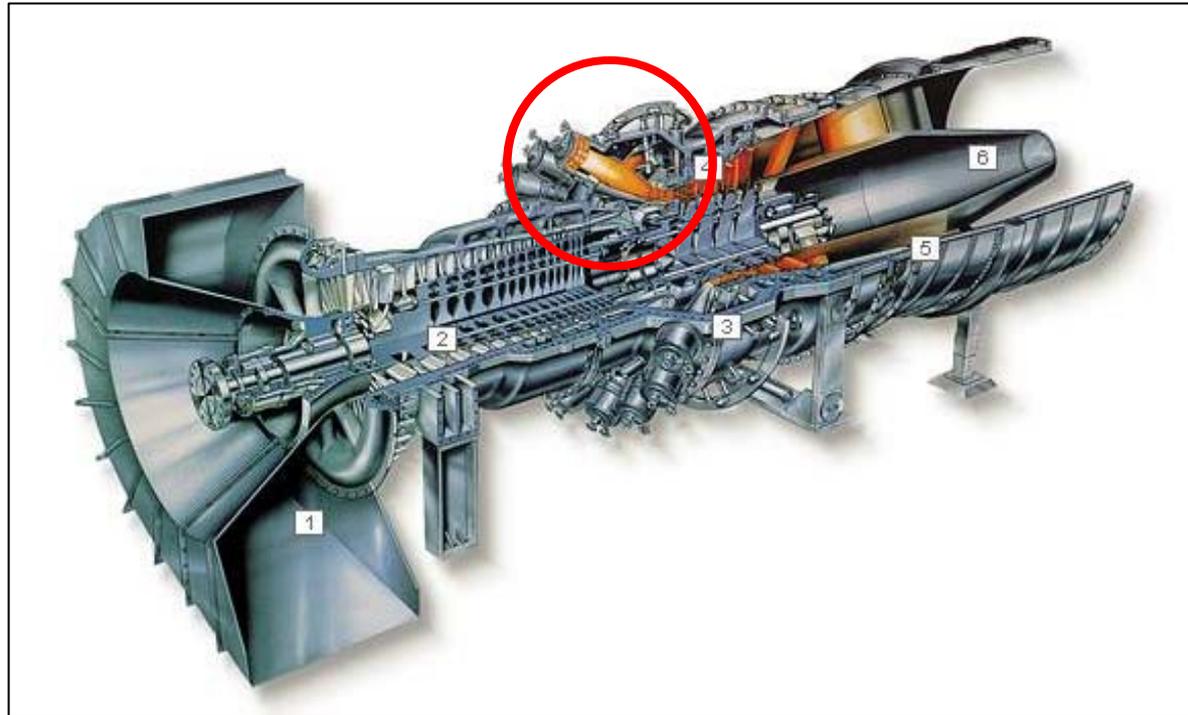
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Overview of Presentation

- Introduction
 - Motivation
 - H₂+N₂ Fuel & TNF
- Previous Work
- Validation Case Parameters
- Experimental Results & CFD
 - Flame zone size and position (CL)
 - OH relative concentration (PLIF)
- Conclusions and Further Work

Introduction



Graphics: Siemens

Power generation with pre-combustion CO₂-capture:

- part of work package 2.3 'H₂-rich combustion' of the EU research project ENCAP (ENhanced CAPture)
- among partners: SINTEF, DLR, ALSTOM, SIEMENS, RWE, VATTENFALL, STATOIL

Motivation

Hydrogen Non-premixed Combustion at Elevated Pressures:

- Premixed H₂-combustion requires very high burner velocities to avoid flashback, this implies large pressure losses in GT-operation
- Little experimental data available for hydrogen combustion under GT-conditions (high pressures), this work provides experimental data for validation of CFD-models

Nitrogen-dilution of the Hydrogen Fuel:

- Reduces reactivity of hydrogen (increase its ignition delay time) for safe operation and avoids burner damage
- Reduces flame temperature and NO_x-formation level
- To be preferred over steam because **a)** steam causes higher metal temperatures of the hot-gas components and **b)** steam increases the cost of operation and ownership, and **c)** within the context of the ENCAP project, N₂ is available from IGCC plant

Previous Work

Hydrogen combustion chemistry benchmarking for pure H₂/O₂ kinetics (Strohle et al. C&F 2006):

- no hydrocarbons considered
- N₂ treated as inert (NO_x chemistry not included)
- N₂ acts as a third body
- high pressure conditions

DLR GT-model burner tested for (Weigand et al. C&F 2006):

- Methane fuel
- Atmospheric conditions

All present measurements performed by Rainer Lücknerath of DLR in Stuttgart (scheduled for publication).

Relevant H₂-CO models

Selected for validation against experimental data at high pressures (Strohle et al. C&F 2006)

Group	Authors	Reactions	Pressure
GRI-Mech	[1.2] Frenklach et al. (1995) [2.11] Bowman et al. (1999) [3.0] Smith et al. (2002)	58	1-2 atm
Dryer	Yetter et al. (1991) Kim et al. (1994) Mueller et al. (1999) Li et al. (2004)	38	0.3-2.2 atm 1-9.6 atm 0.3-15.7 atm 0.3-87 atm
Ó Conaire	Ó Conaire et al. (2004)	42	0.05-87 atm
Warnatz	Baulch et al. (1991) Warnatz (2004)	38	
Leeds	Hughes et al. (2001)	46	

H₂/O₂ Turbulent Combustion Modeling

SPIDER (SINTEF):

- EDC combustion model and detailed chemical kinetics solver already present
- H₂-combustion implemented comparing several detailed mechanisms (Li, GRI-Mech, Warnatz...)

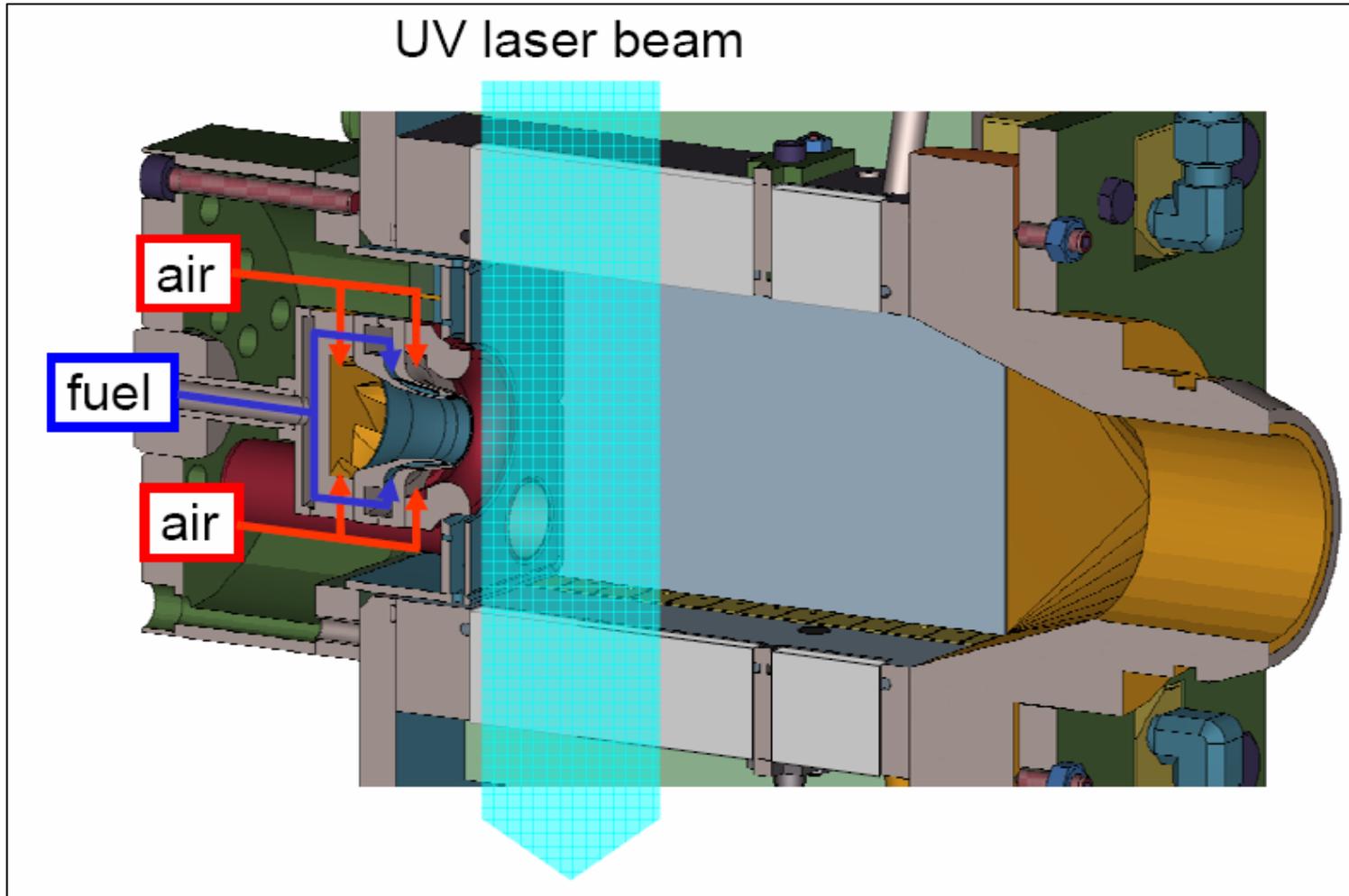
FLUENT (for ALSTOM):

- EDC combustion model present
- No external stiff-equations solver implemented (use built-in solver)
- H₂-combustion implemented in a 11-step reduced mechanism

CFX (for SIEMENS):

- EDC combustion model implemented
- Detailed chemical kinetics solver implemented as user library (including LIMEX and ChemKin)
- H₂-combustion implemented in a 11-step reduced mechanism

Case Configuration (1)



Graphics: DLR (Rainer Lückerrath)

- Two co-rotating swirl generators for the air supply
- One annular multi-channel ring injector in between the swirled flows
- Maximum thermal power up to 1.3 MW
- CL and PLIF of flame @ 5, 10, 20 bars

Case Configuration (2)

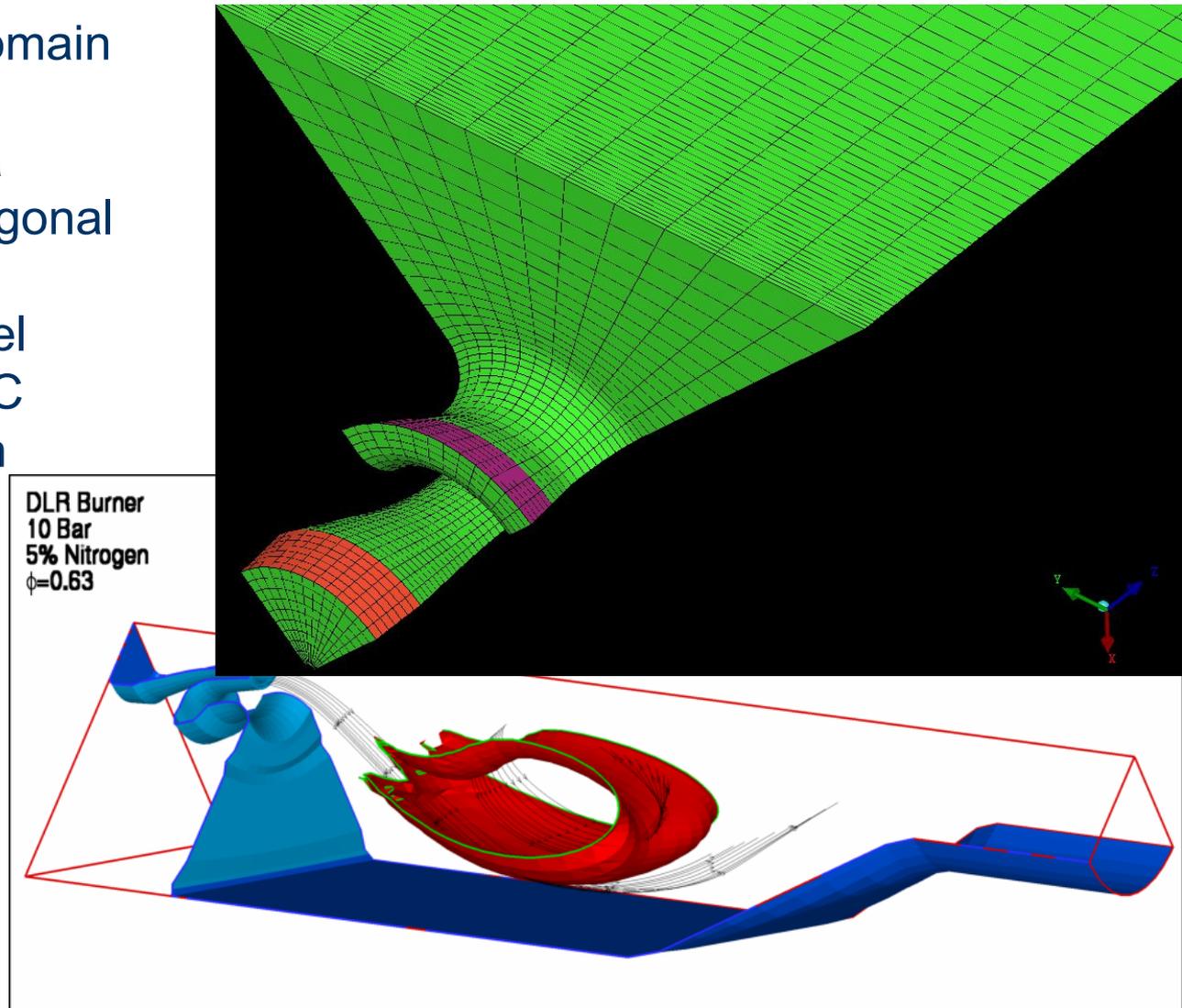


Gas supply!

Graphics: DLR (Rainer Lückerath)

Case Configuration (3)

- ¼ of the physical domain is simulated
- FV CFD-solver on a structured non-orthogonal mesh
- k-e turbulence model coupled with the EDC turbulent combustion model
- 11-step reduced hydrogen chemistry



Flame Dependency on Dilution Level (1)

$H_2=60\%$, $N_2=40\%$

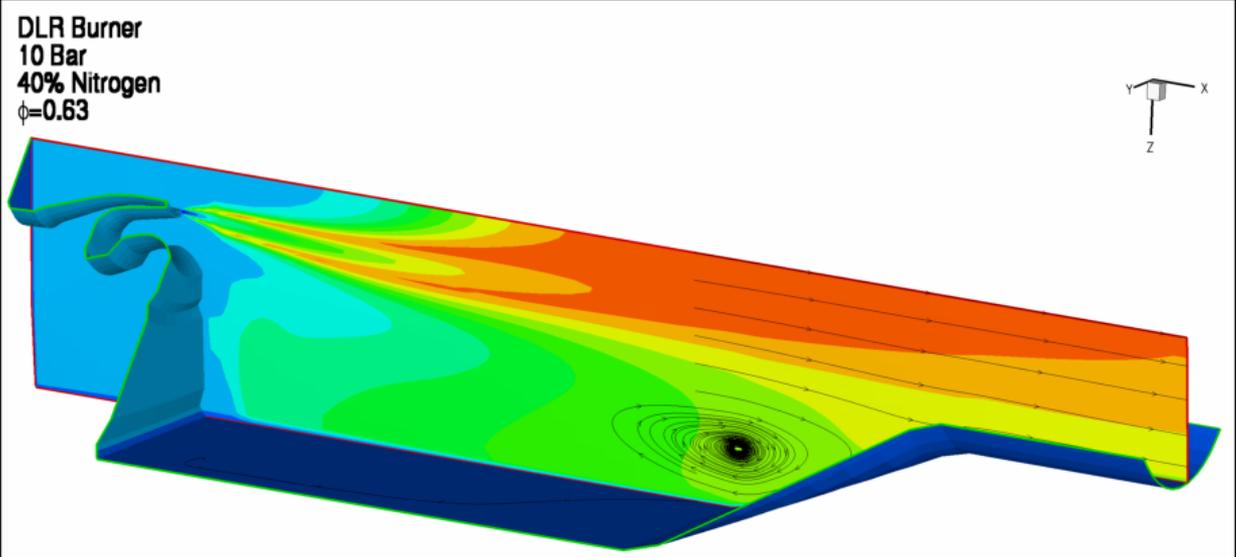


$H_2=95\%$, $N_2=5\%$

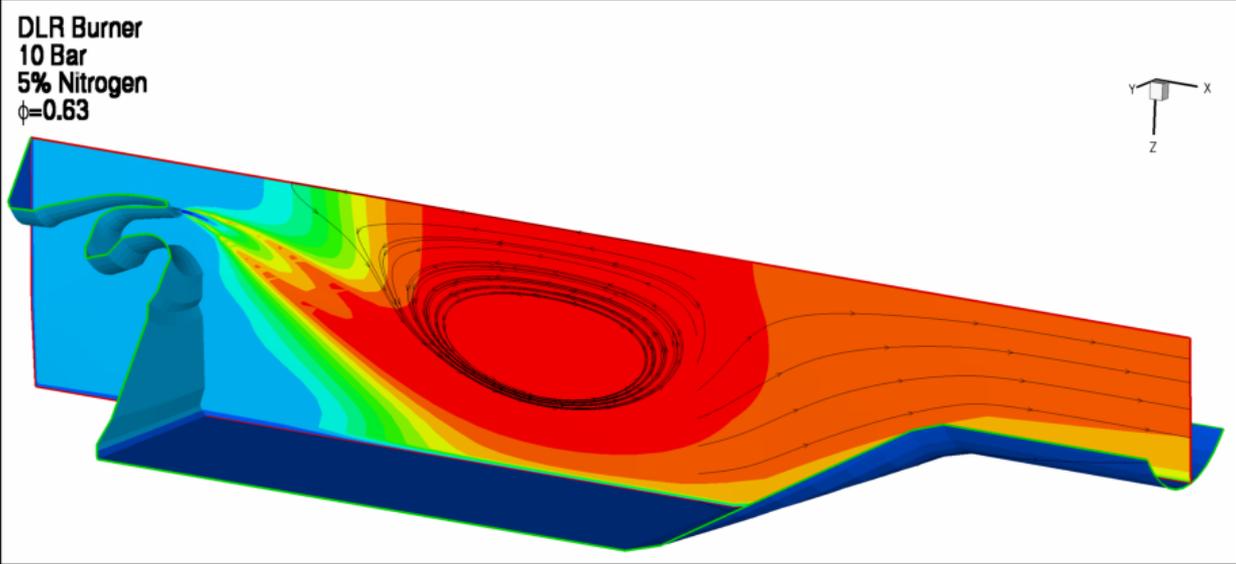


Graphics: DLR (Rainer Lückerrath)

Flame Dependency on Dilution Level (2)

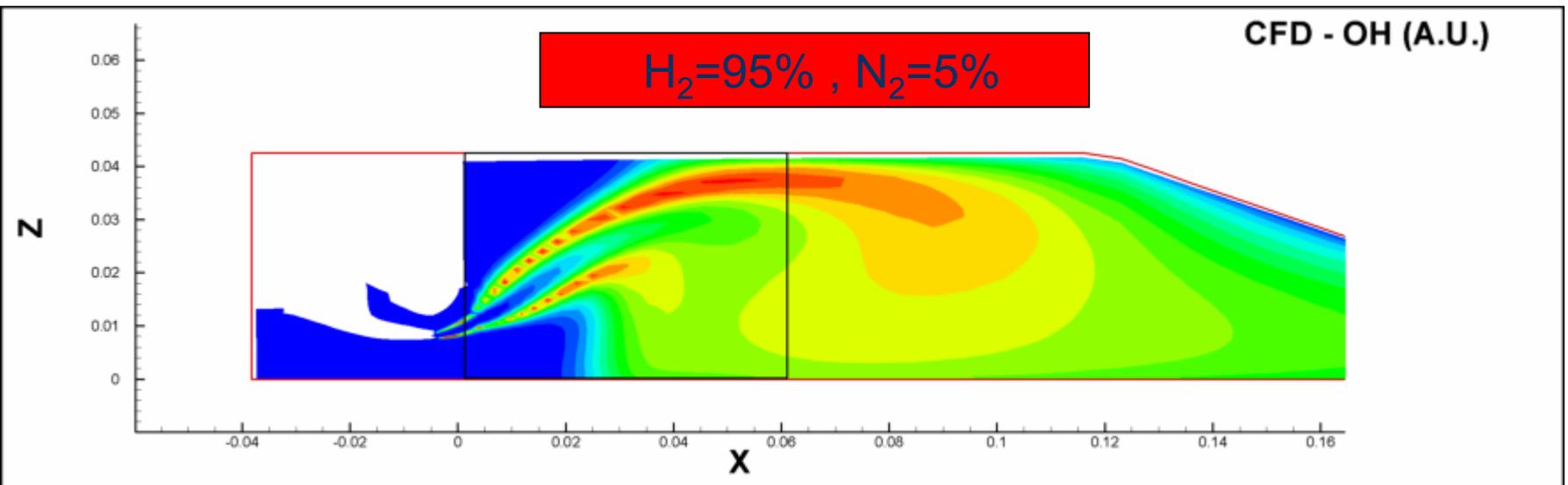
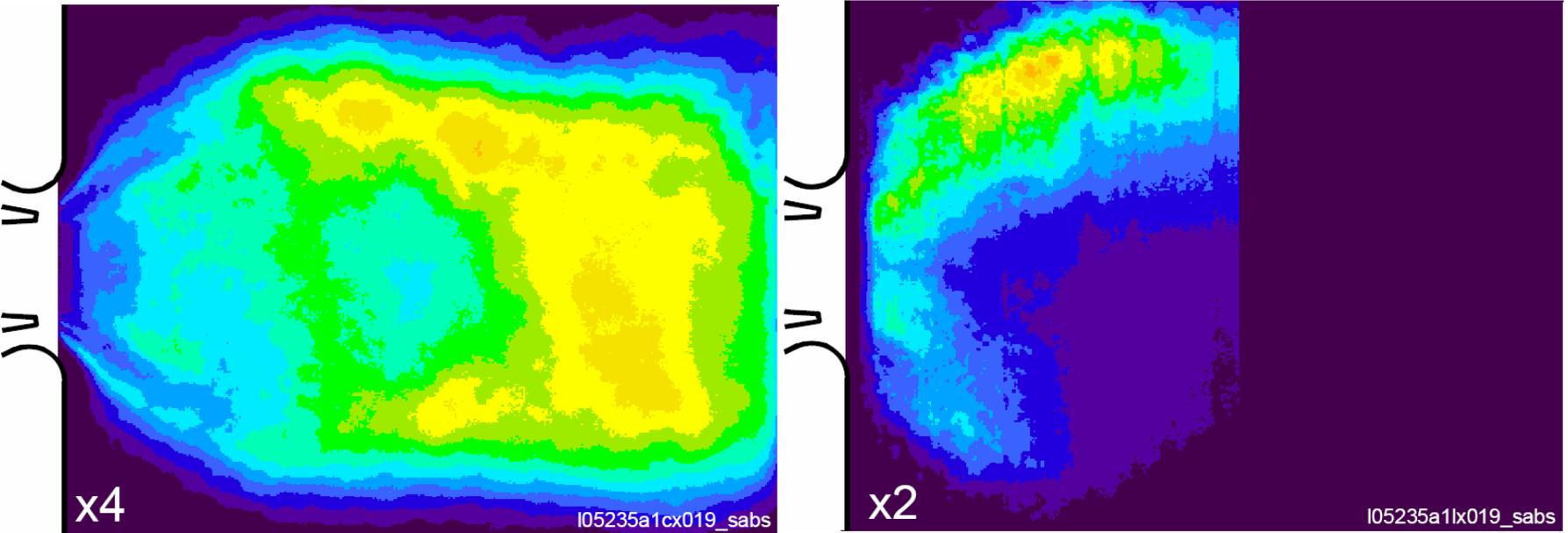


H₂=60% , N₂=40%

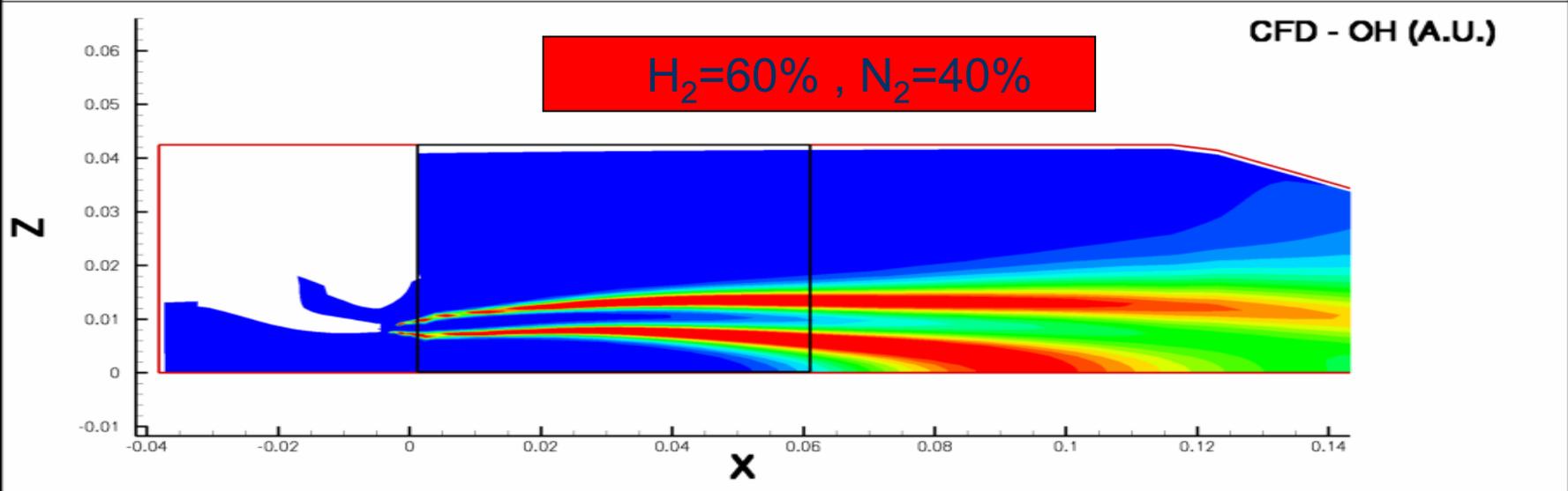
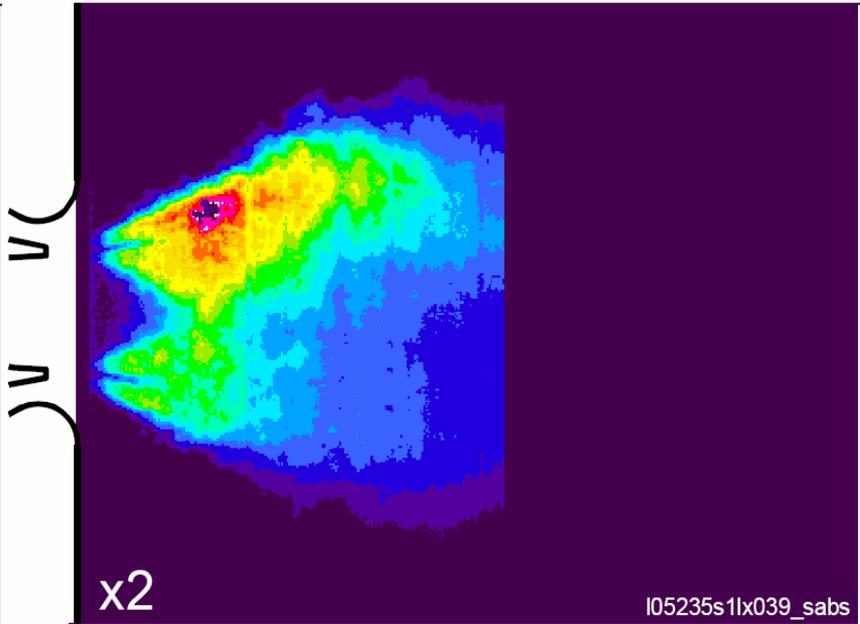
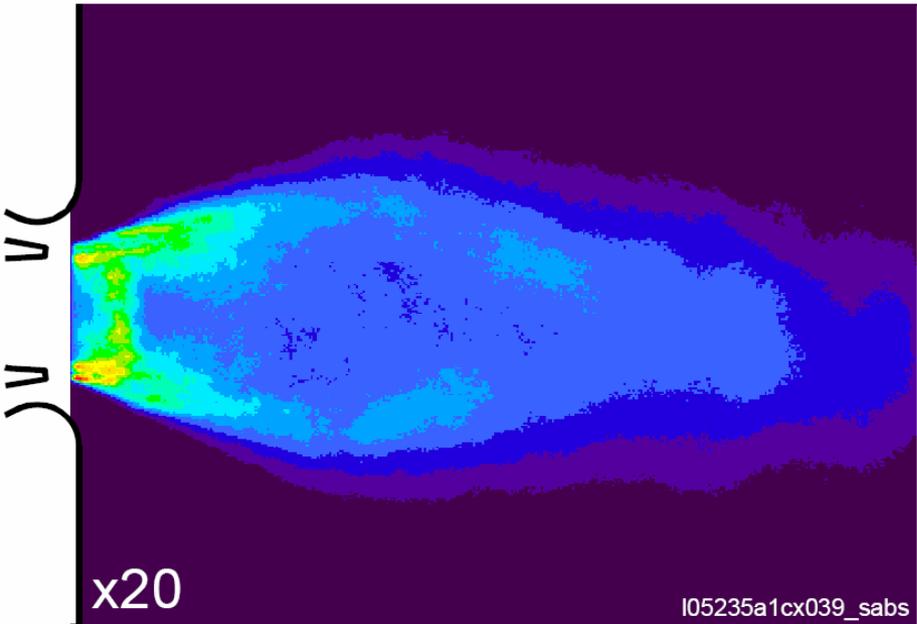


H₂=95% , N₂=5%

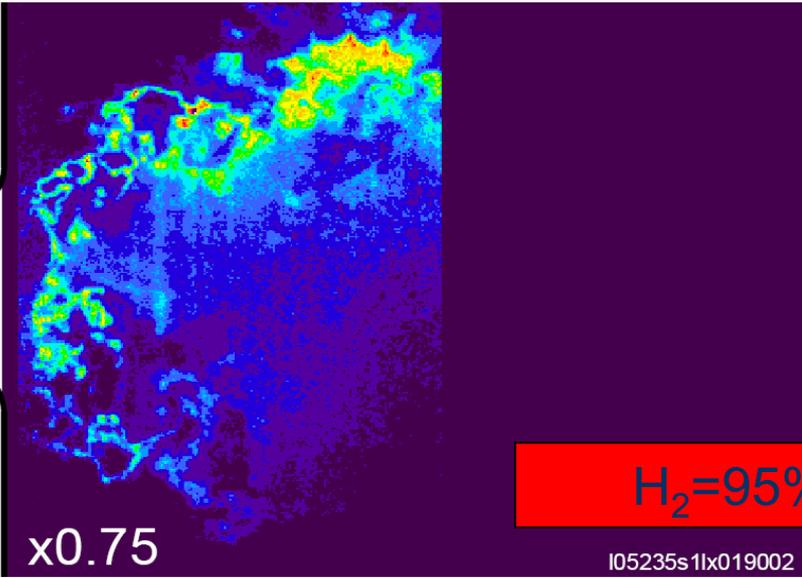
Flame Dependency on Dilution Level (3)



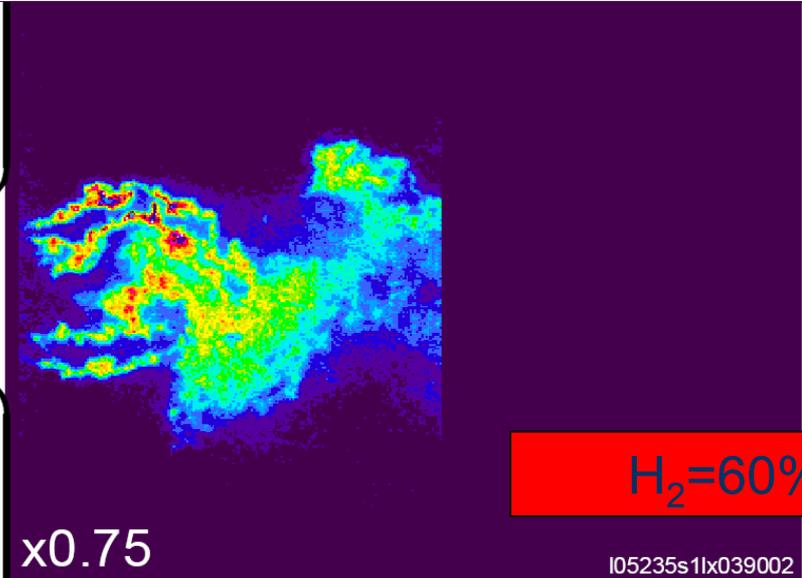
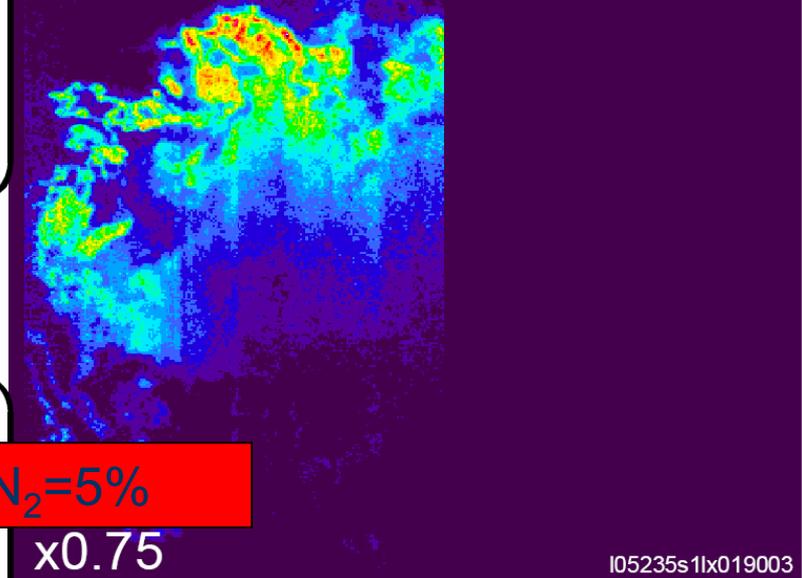
Flame Dependency on Dilution Level (4)



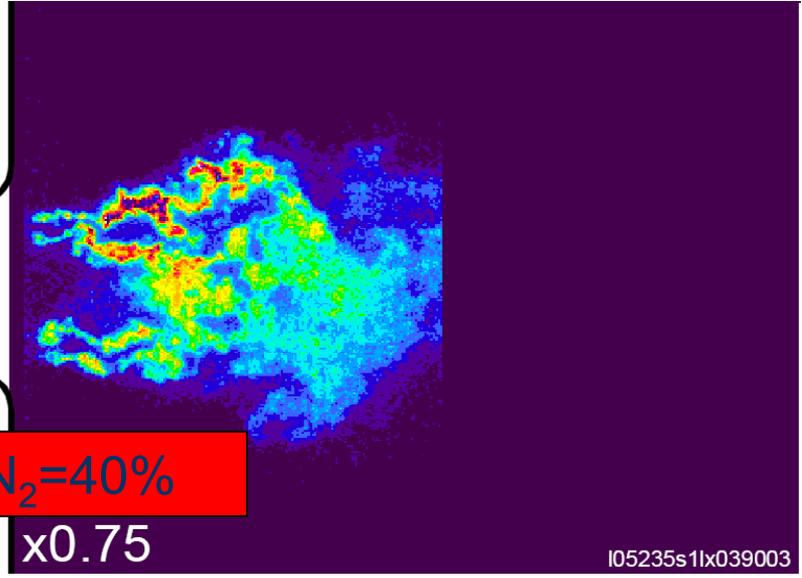
Flame Dependency on Dilution Level (5)



H₂=95% , N₂=5%



H₂=60% , N₂=40%

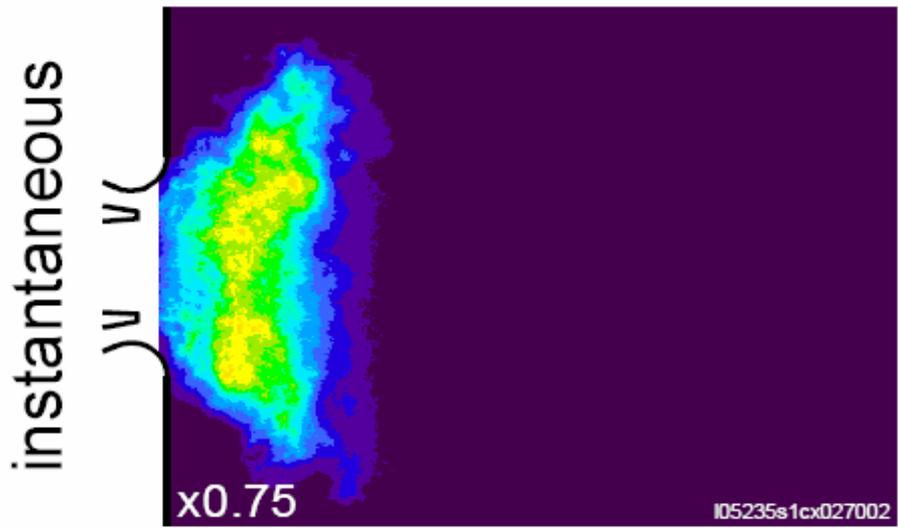
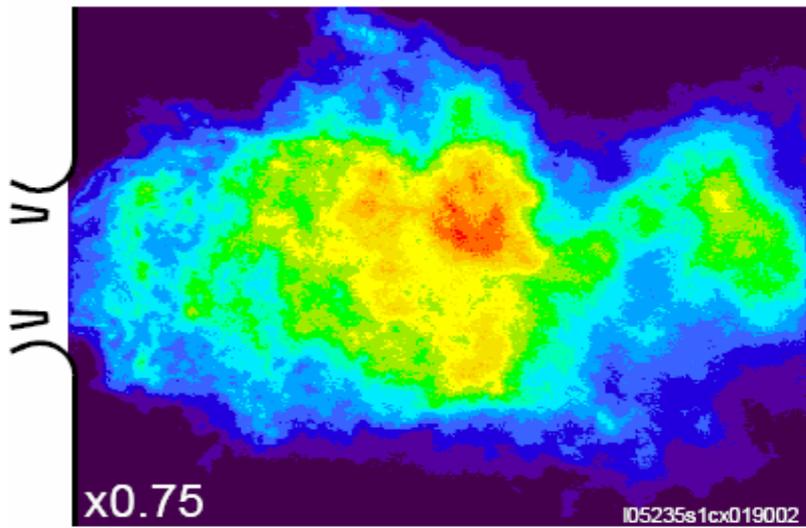
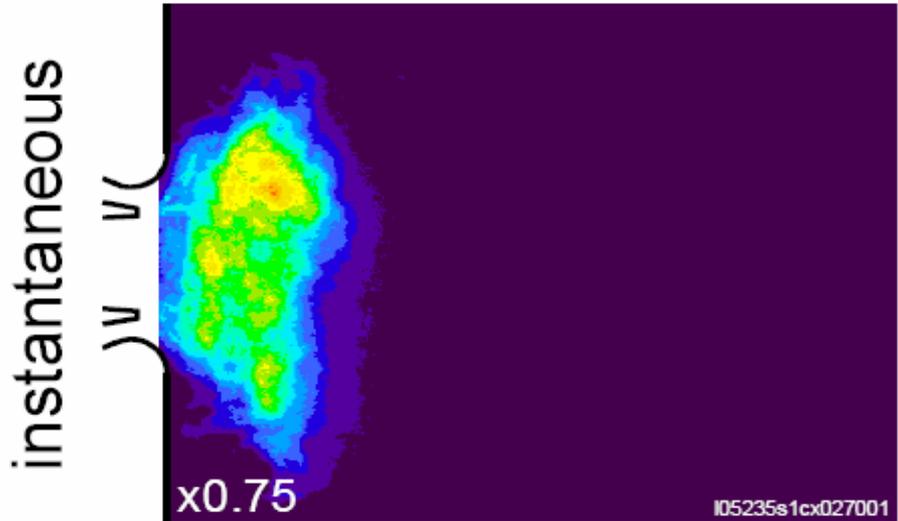
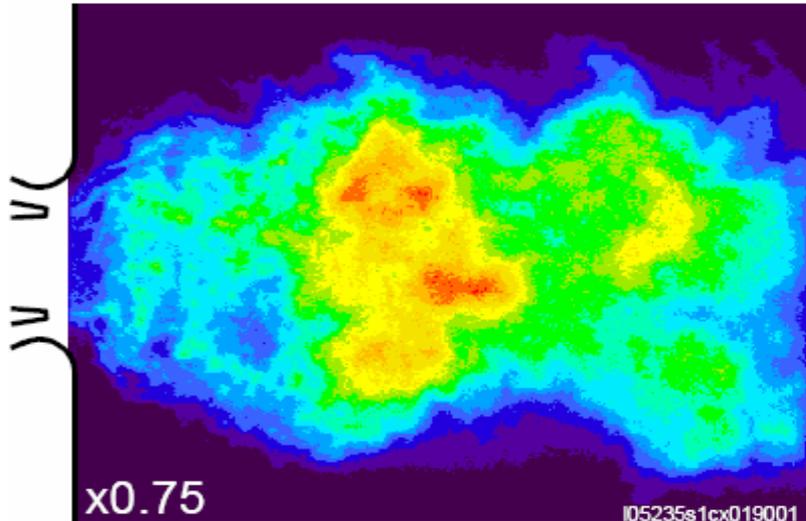


Flame Dependency on ϕ (1)

$H_2=95\%$, $N_2=5\%$

richer flame

leaner flame

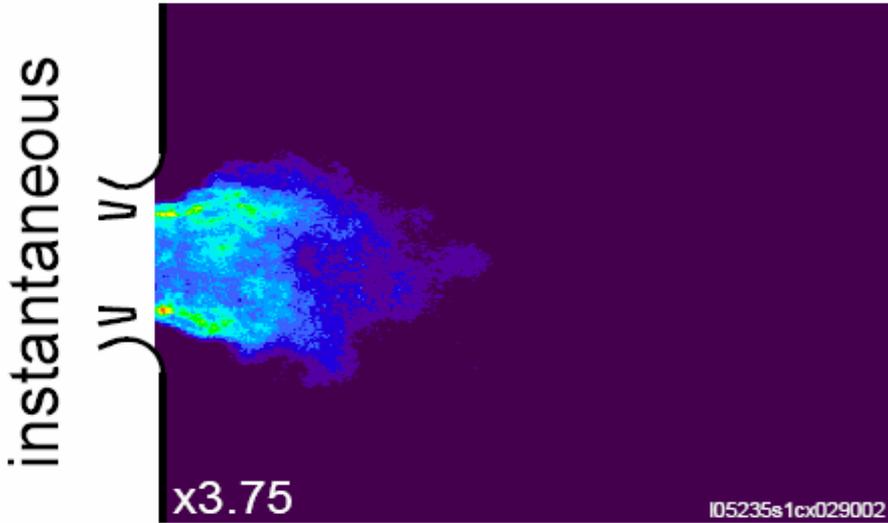
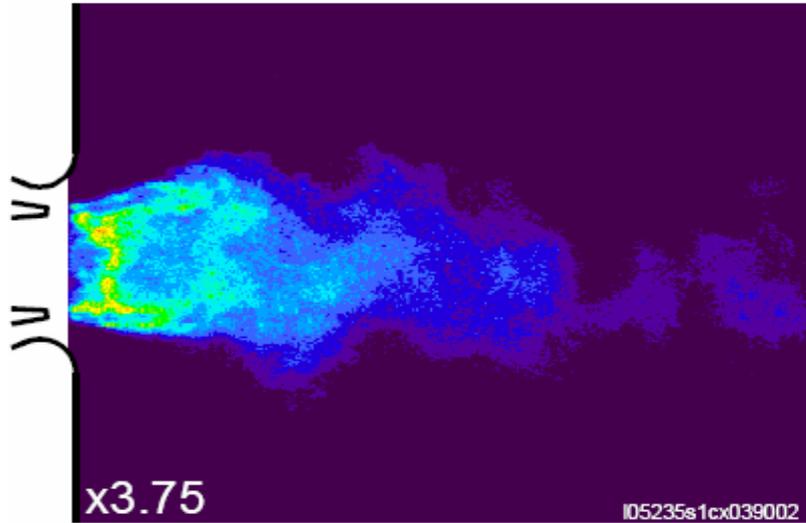
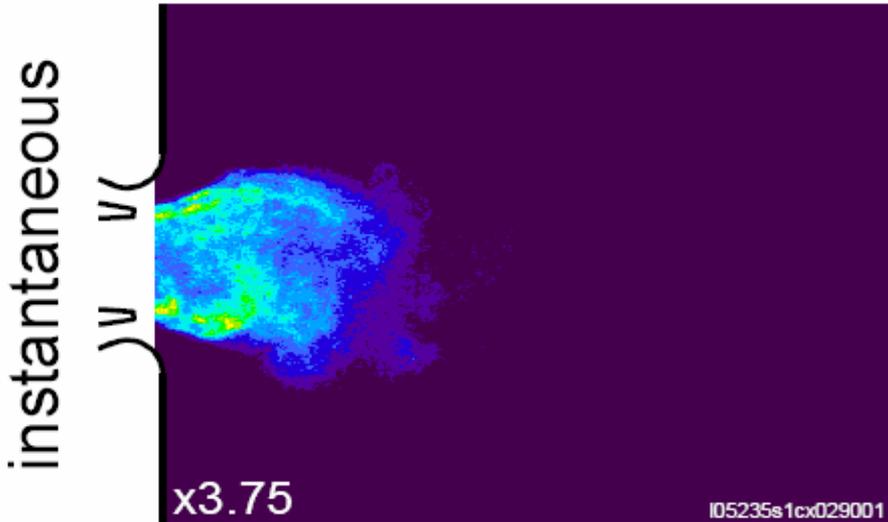
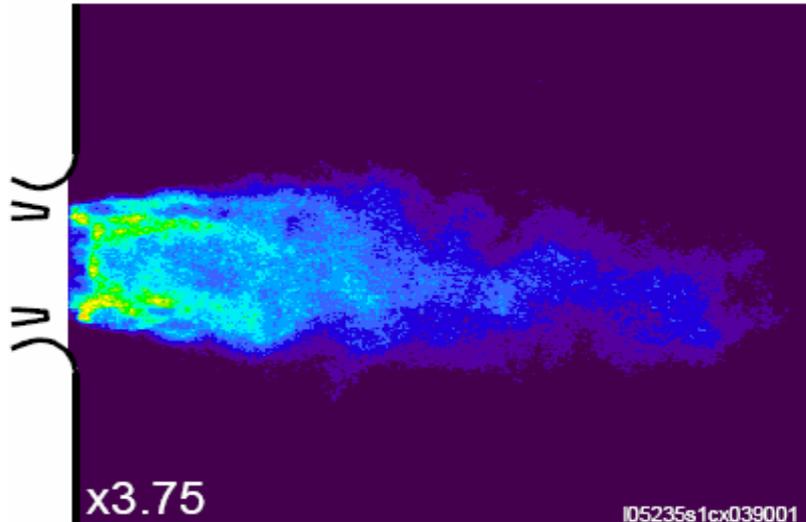


Flame Dependency on ϕ (2)

$H_2=60\%$, $N_2=40\%$

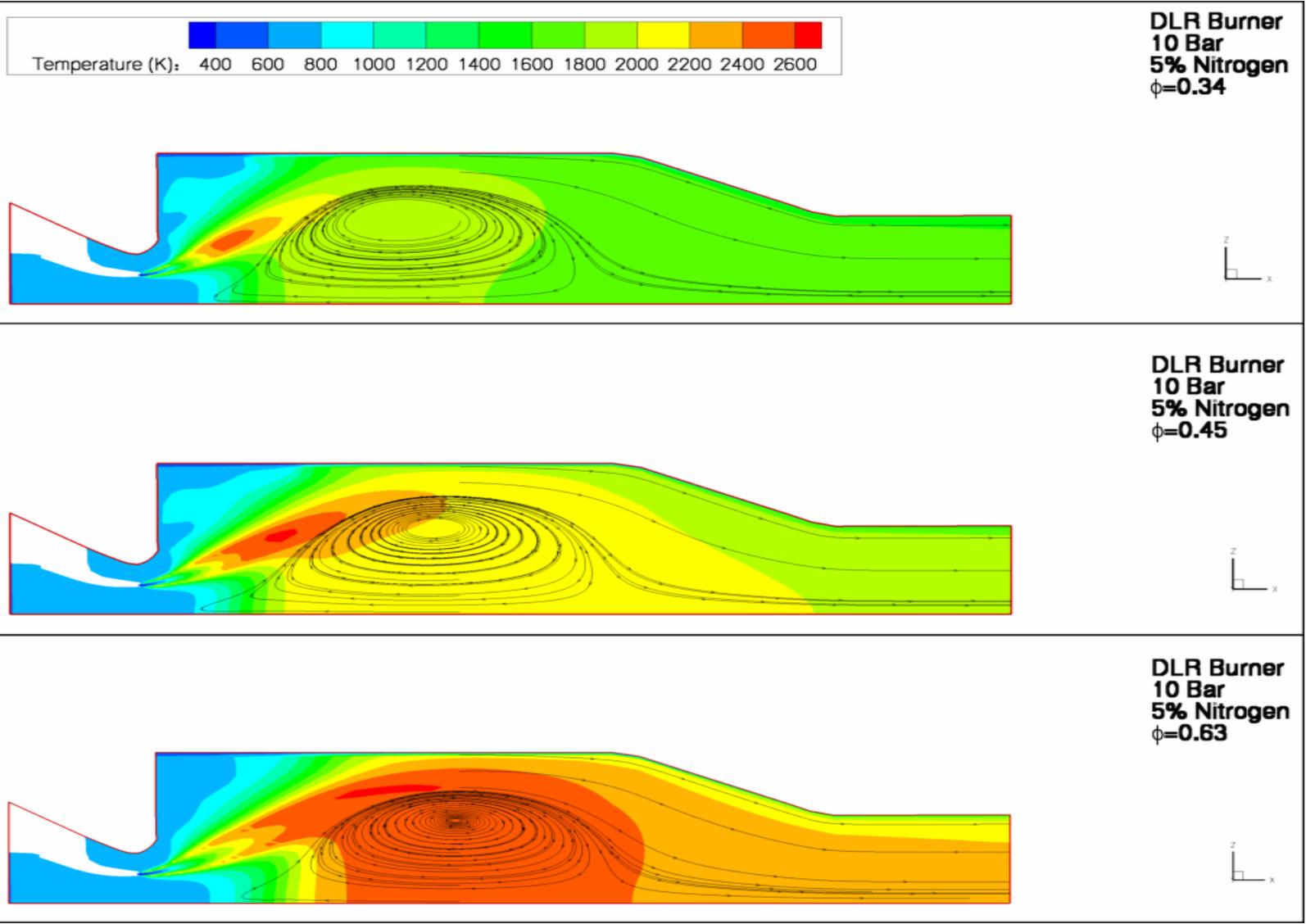
richer flame

leaner flame



Flame Dependency on ϕ (3)

$H_2=95\%$, $N_2=5\%$



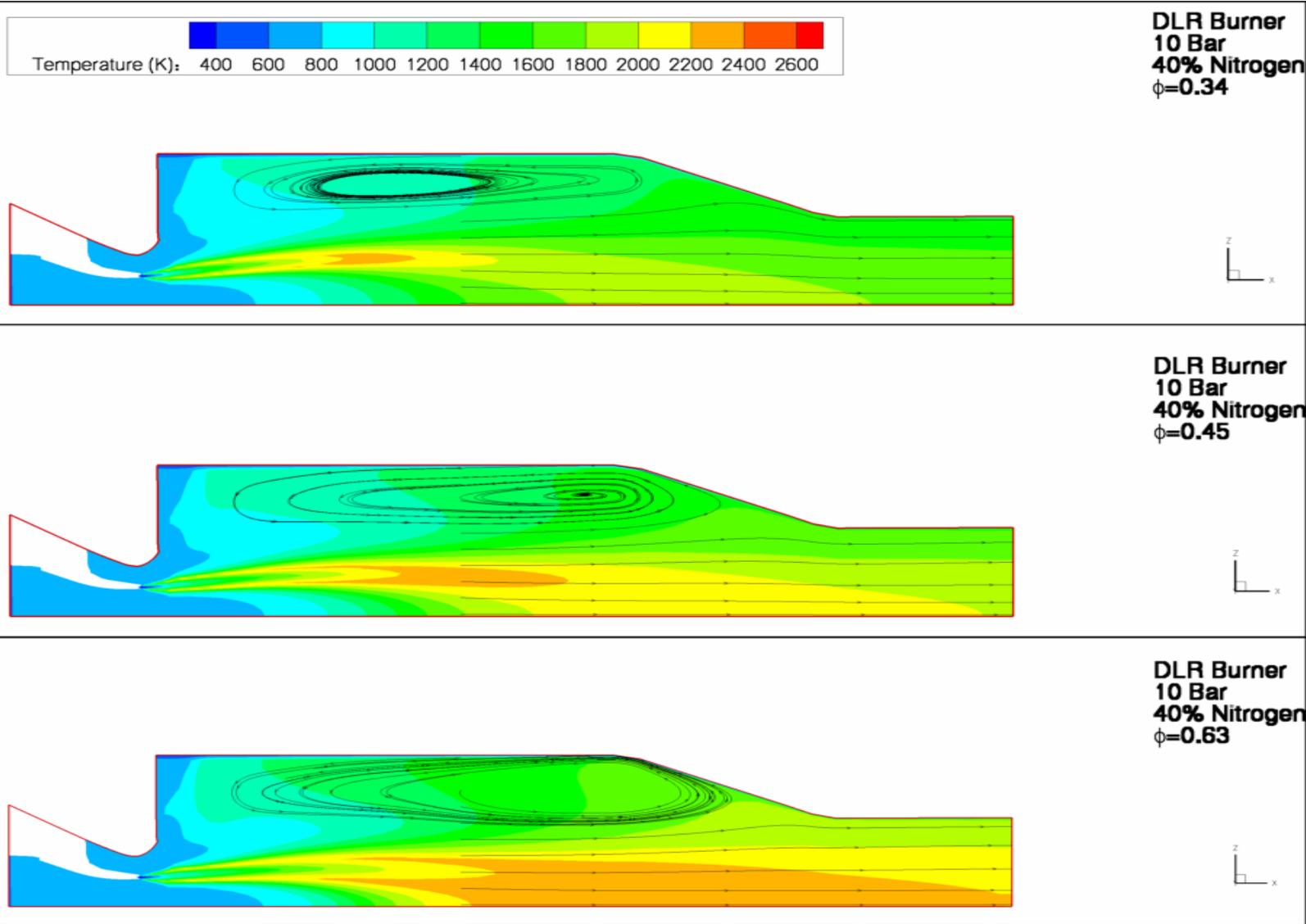
leaner flame

richer flame



Flame Dependency on ϕ (4)

$H_2=60\%$, $N_2=40\%$



leaner flame

richer flame



Conclusions and Further Work

- Flame shape, position and structure seems to be well captured by the CFD
- Flame is strongly dependent on the dilution level resulting in a classical swirl-flame for the 5%-dilution case (low fuel axial momentum) and in a jet-flame for the 40%-dilution case (high fuel axial momentum)
- No large effect of pressure on the flame shape and position is observed between 10 and 20 bars operating conditions
- No blow-off limit found even for very lean conditions ($\varphi \sim 0.3$) both in experiments and simulations
- No significant pulsation or flame instability could be detected
- NO_x level between several hundred ppm (@ 15% O_2) for the 5%-dilution case and 6 ppm for the leanest 40%-dilution case
- Simulations with the 11-steps reaction mechanism gives significantly lower peak temperatures and thus NO formation compared to the infinitely fast chemistry assumption
- Glarborg model (simple data postprocessing) gives correct order of magnitude estimates for NO-formation rate
- CARS temperature measurements are the next task at DLR

Thank you for your attention!