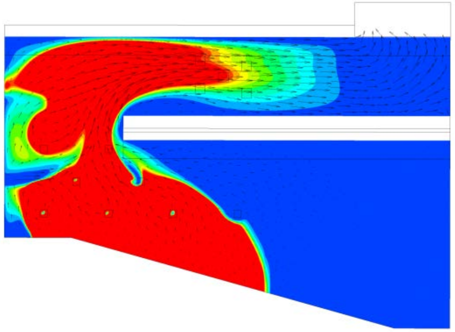


Moving Grate Combustion Optimisation with CFD and PIV

(Particle Image Velocimetry)

Thomas Nussbaumer

Martin Kiener

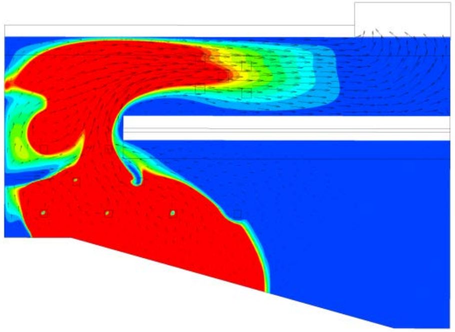
Bioenergy Research Group

Lucerne University of Applied Sciences

Verenum

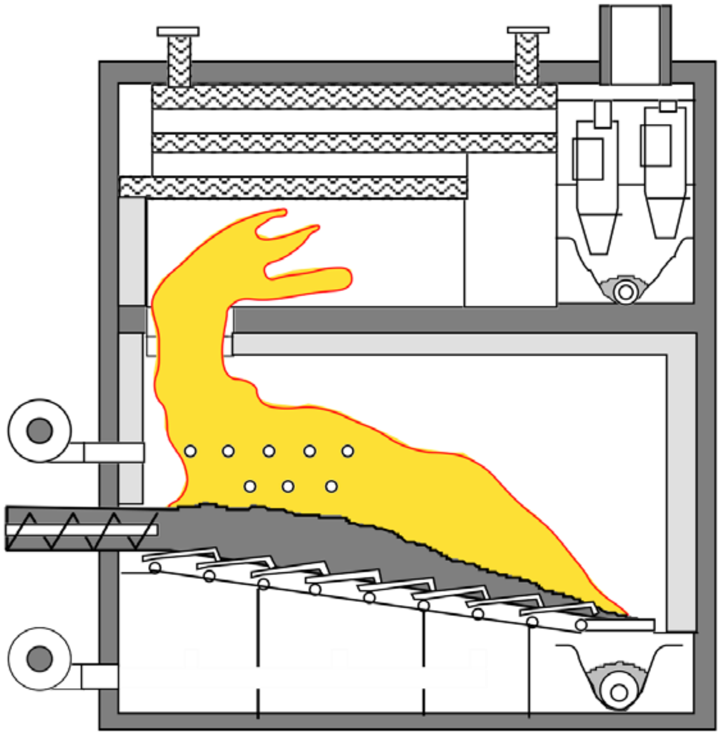
Hochschule Luzern

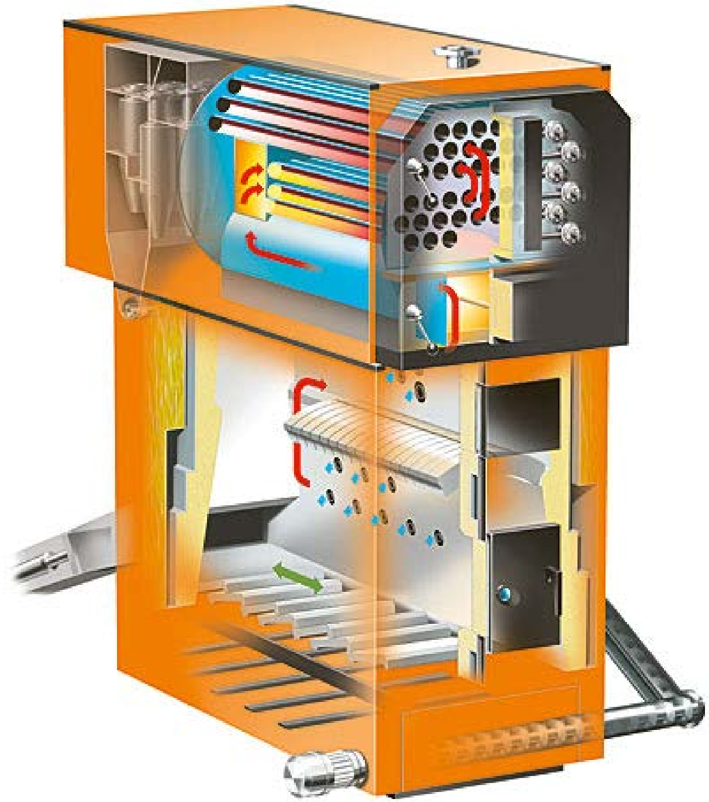
Technik & Architektur



1. Introduction
2. Target
3. Optimisation with CFD
4. Comparison with PIV
5. Experiments on a 1.2 MW boiler
6. Conclusions

Moving grate boiler for biomass





Graph: Schmid energy solutions

Boiler capacity	500 kW – 50 MW
Fuel moisture	10% – 60% (of wet mass)
Ash content	0% – >10%

Limitations in practical operation

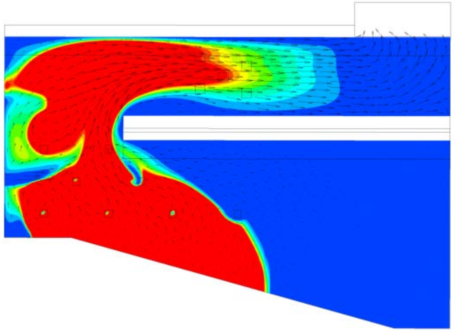
Load range for continuous operation from 40% – 100%

Consequence 1: Intermittent on/off operation at lower load

- Start phases cause increased emissions
- ESP or fabric filters may be off or in bypass

Consequence 2: Increase of CO and VOC at part load

- Interest to identify the reason(s):
  Mixing, temperature, uneven fuel distribution, others?



1. Introduction
2. Target
3. Optimisation with CFD
4. Comparison with PIV
5. Experiments
6. Conclusions

The target is...

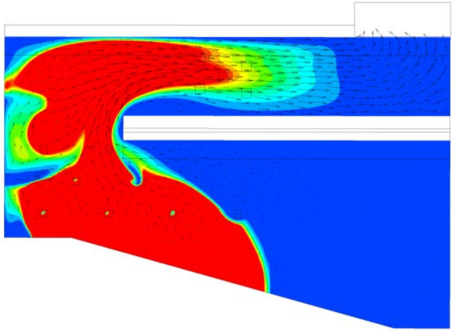
... to optimise the combustion

to ascertain low excess air and high efficiency and

... to improve the part load capability with increasing the load range to < 30% – 100%

... by aerodynamic optimisation, i.e.,

1. secondary air injection and
2. optionally with flow obstacles.



Method

1. Solid Biomass conversion to gases (CO, CO_2, H_2, H_2O, CH_4) and char is calculated by a one-dimensional transient integral model in adaptation to [1] currently refined by [2]

2. Gas phase modelled with CFD by use of k-ε and EDM

3. Boundary conditions for the reference case:

Thermal firing capacity	1.4 MW
Boiler efficiency	85%
Fuel humidity	50%
Primary- and secondary air temperature	80°C
Excess air ratio	
Primary air λ_{PA}	0.72
Secondary air 1 λ_{SA1}	0.86
Secondary air 2 λ_{SA2}	0.22
Total: $\lambda_{tot} = \lambda_{PA} + \lambda_{SA1} + \lambda_{SA2}$	1.80

[1] T. Klasen, K. Görner, 2nd int. Symp. On Inc. And Flue Gas Treatm., Sheffield 4.-6.7.1999
[2] J. Martinez, T. Nussbaumer, Poster 2 DV 3.61

Fluid dynamic parameters

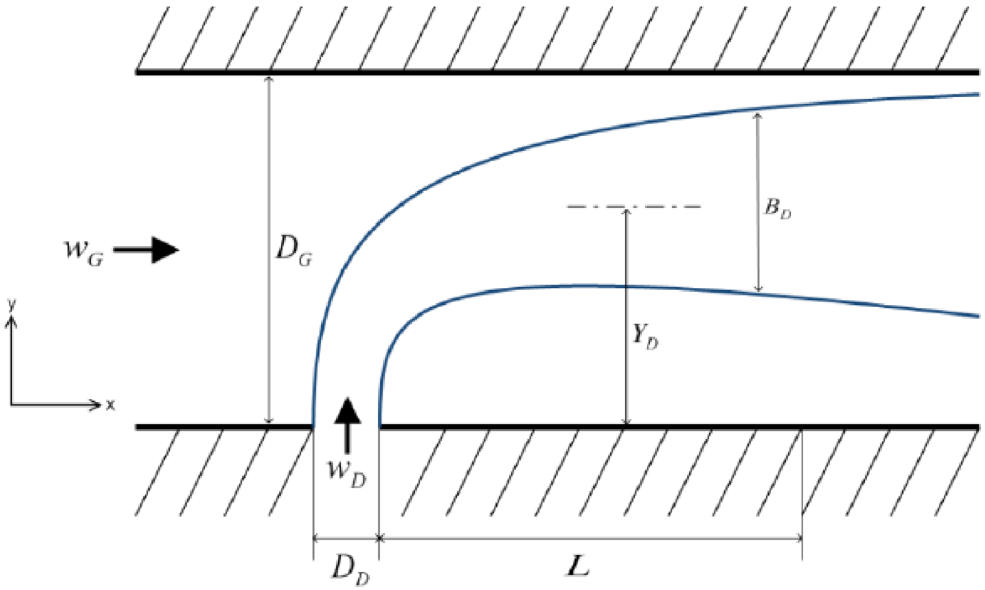
Requirement 1: Turbulence $Re = \frac{u \cdot L}{\nu} > 2300$

a) Design for turbulent flow
(here ascertained as Re>>2300

b) For PIV: $Re_{Model} = Re_{Reality}$

Fluid dynamic parameters

Requirement 2: For Mixing two fluid flows:
Jet In Cross Flow, JICF [1,2]



[1] Schlüter, J.U.; Schönfeld, T.: *Flow, Turbulence and Combustion*, 65: 177-203; 2000
[2] Suman, M, Thesis, University of Minnesota, USA; 2006]

Fluid dynamic parameters

Requirement 2: For Mixing two fluid flows:
Jet In Cross Flow, JICF [1,2]

Impulse Ratio between flows
= ratio of imp. current densities

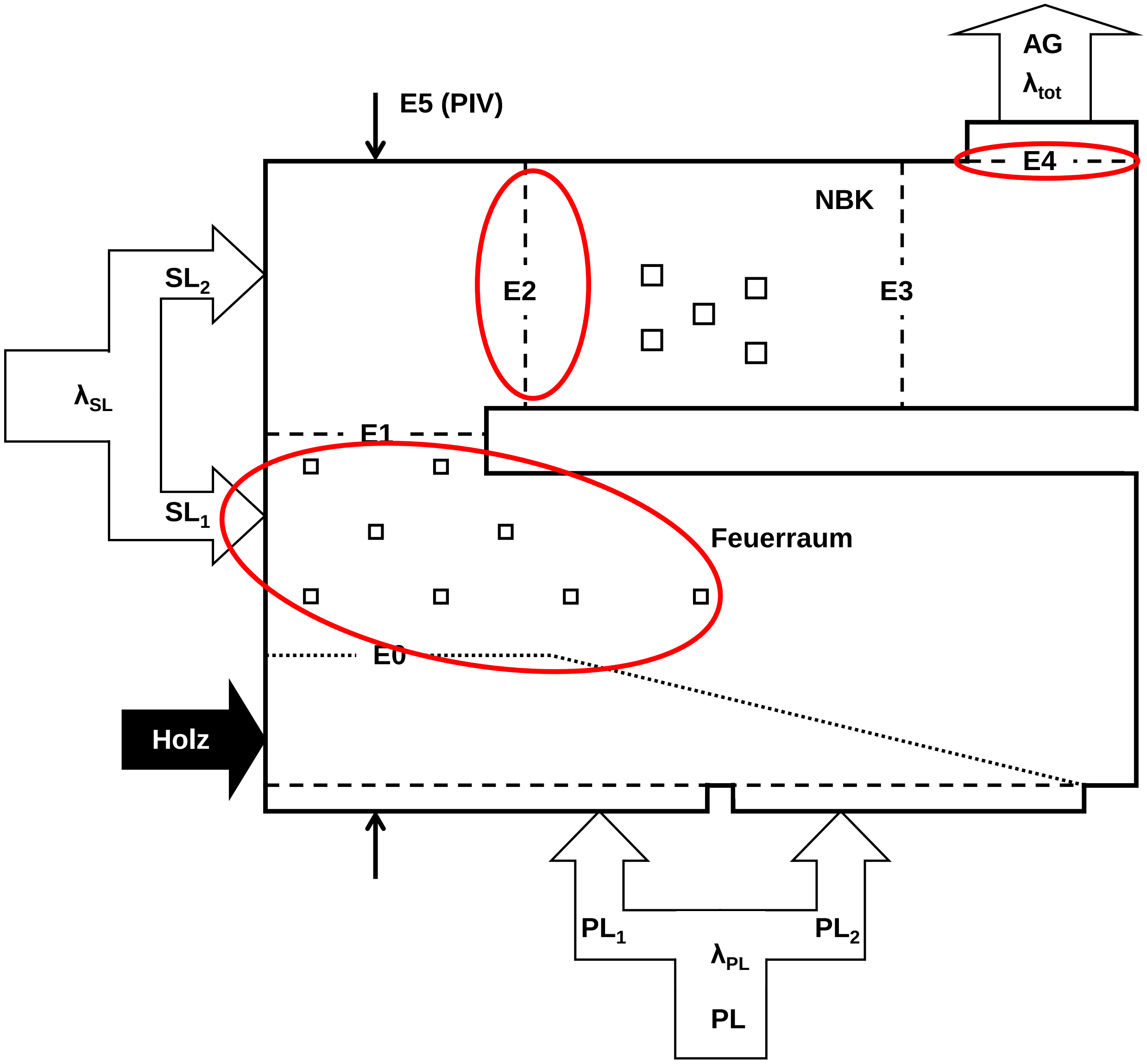
$$IR_{JM} = \sqrt{\frac{\rho_J \cdot u_J^2}{\rho_M \cdot u_M^2}}$$

a) Design for optimum IR
b) For PIV: $IR_{Model} = IR_{Reality}$

u_J velocity of jet flow [m/s]
u_M velocity of main flow [m/s]
ρ_J density of jet flow [kg/m³]
ρ_M density of main flow [kg/m³]

[1] Schlüter, J.U.; Schönfeld, T.: *Flow, Turbulence and Combustion*, 65: 177-203; 2000
[2] Suman, M, Thesis, University of Minnesota, USA; 2006]

CFD Analysis



Verenum

Hochschule Luzern
Technik & Architektur

Results CFD: 1. Full load / part load

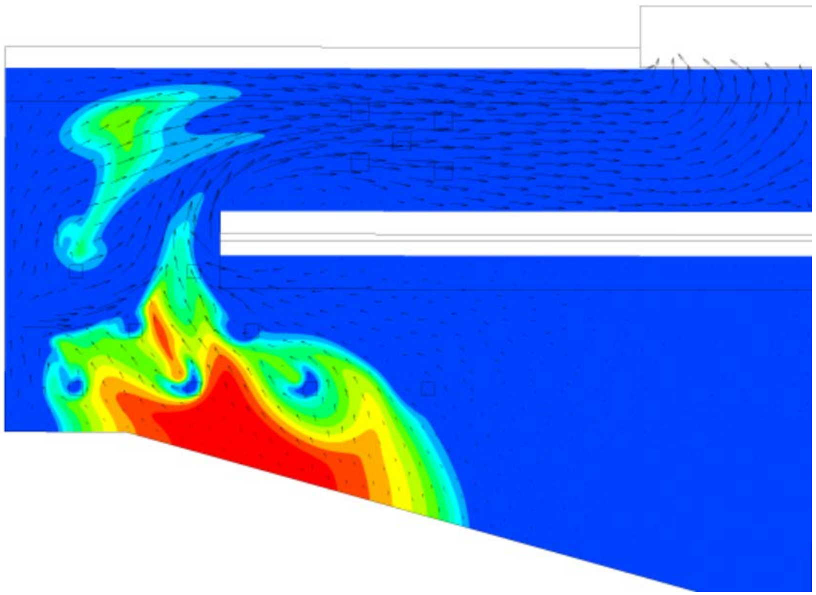
CO (part load) < CO (nominal load)

Explanation:
– Impulse ratio remains constant
– Turbulence is ensured also at part load

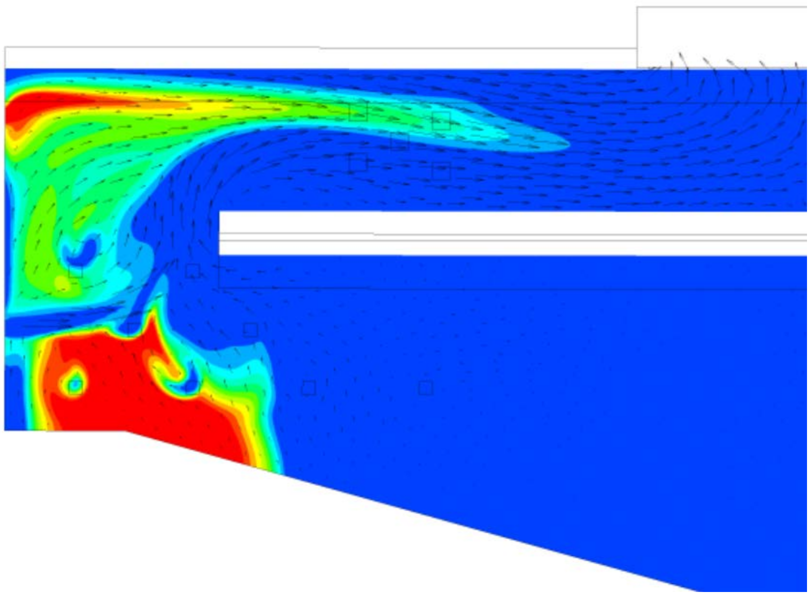
However, only at identical boundary conditions, i.e.,
– temperature,
– excess air ratio, and
– grate coverage

Results CFD: 2. Grate coverage

Reference case



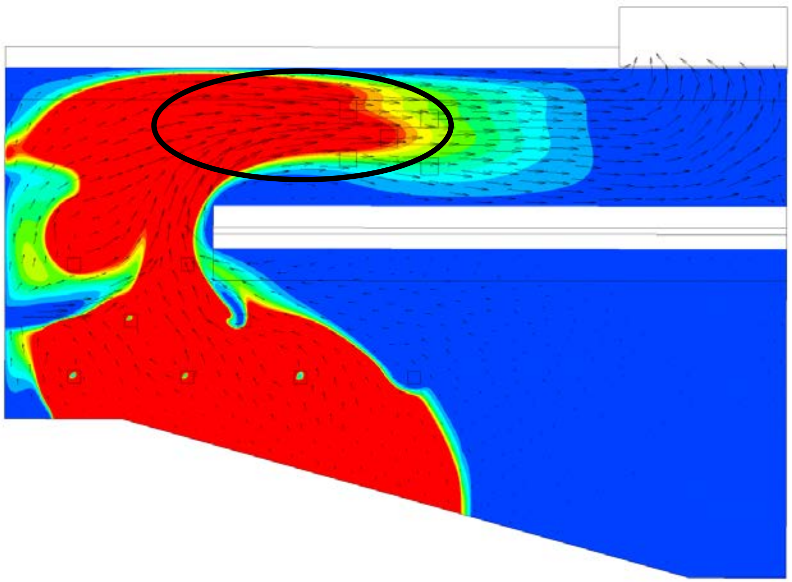
Grate fully covered



Second half uncovered

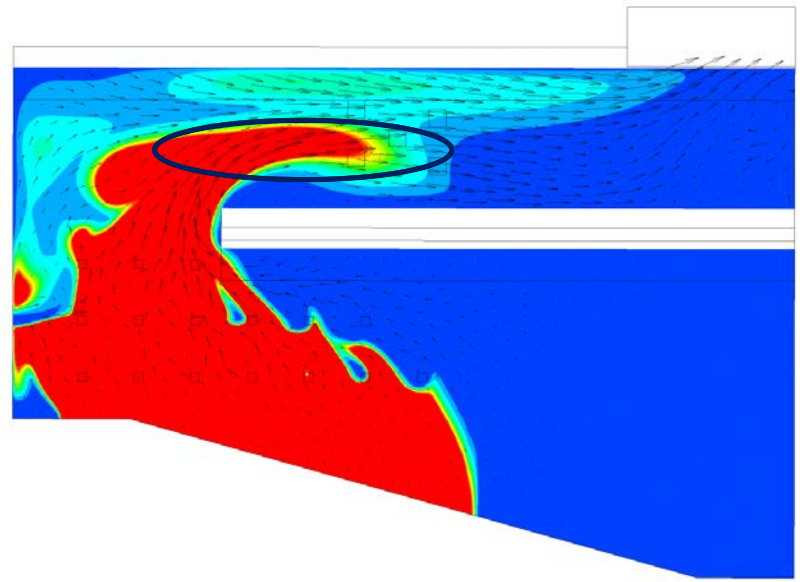
Results CFD: 3. Secondary air injection

Reference case



$N = 1$
$A = 1$
$\Delta p = 100\%$
$CO_{P4} = 100\%$

Case SL-8



$N = 2$
$A = 1$
$\Delta p = 97\%$
$CO_{P4} = 42\%$

Selection of cases for experiments
1. Secondary air injection

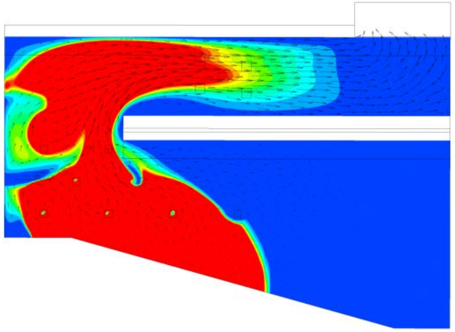
Case	EXP	N/N_{ref} [-]	$A_N/A_{N,ref}$ [-]	$A_{tot}/A_{tot,ref}$ [-]	ir_{norm} [-]	CO/CO_{ref} [%]	ME/ME_{ref}* [%]	$\Delta p/\Delta p_{ref}$ [%]
SA-1		1	1	0.125	8	0.1	99	6630
SA-2		1	0.25	0.25	4	2	100	1647
SA-3	+	1	0.5	0.5	2	21	101	405
Ref	+	1	1	1	1	100	100	100
SA-4		1	2	2	0.5	252	96	23
SA-5		2	0.0625	0.125	8	0.1	92	6464
SA-6		2	0.125	0.25	4	0.1	100	1683
SA-7		2	0.25	0.5	2	3	98	405
SA-8	+	2	0.5	1	1	42	97	97
SA-9		2	1	2	0.5	199	95	23
SA-10	+	1.5	0.5	0.75	1.33	–	–	–

*ME = Mixing Efficiency: The local mixing quality of two flows is defined as difference between the local tracer concentration and the mean tracer concentration of a fully mixed flow

[Baillifard, M. et al.: 16th EU Conf., Valencia, 2–6 June 2008]

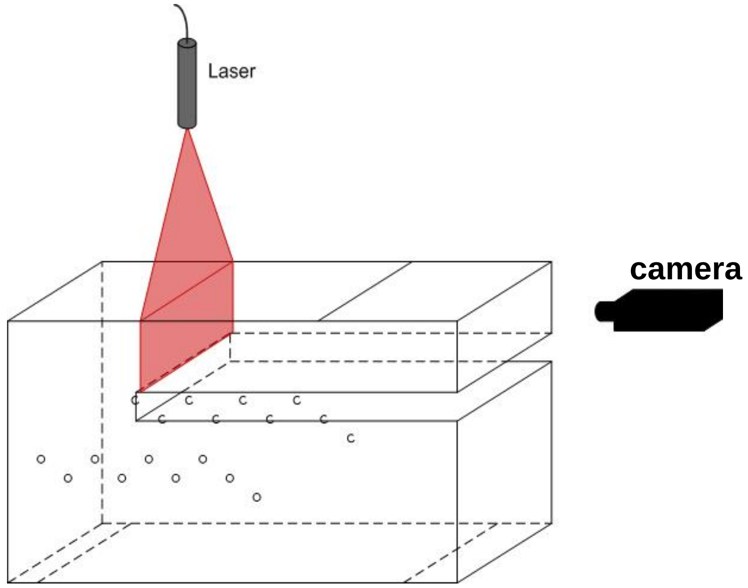
Selection of cases for experiments
2. Obstacles

Case	EXP	Variation	CO/CO_{ref} [%]	ME/ME_{ref} [%]	$\Delta p/\Delta p_{ref}$ [%]
Ref	+	No	100	100	100
O-1		Narrow deflection	26	105	138
O-2	+	Obstacle middle	27	103	132
O-3		Obstacle after SA_2	106	99	103
O-4	+	Obstacle side	20	106	141
O-5		Asym. obstacle in PCC	57	103	137
O-6		Neck in P1	38	104	113
O-7		Nose before deflection	126	98	97
O-8	+	Obstacle ceiling	11	104	222



1. Introduction
2. Target
3. Optimisation with CFD
4. Comparison with PIV
5. Experiments
6. Conclusions

Particle Image Velocimetry (PIV)



1. Flow seeding by tracer aerosols (1 μm)
   – for flow field detection in general
   – in one flow of two for mixing process

2. Illumination of plane with laser

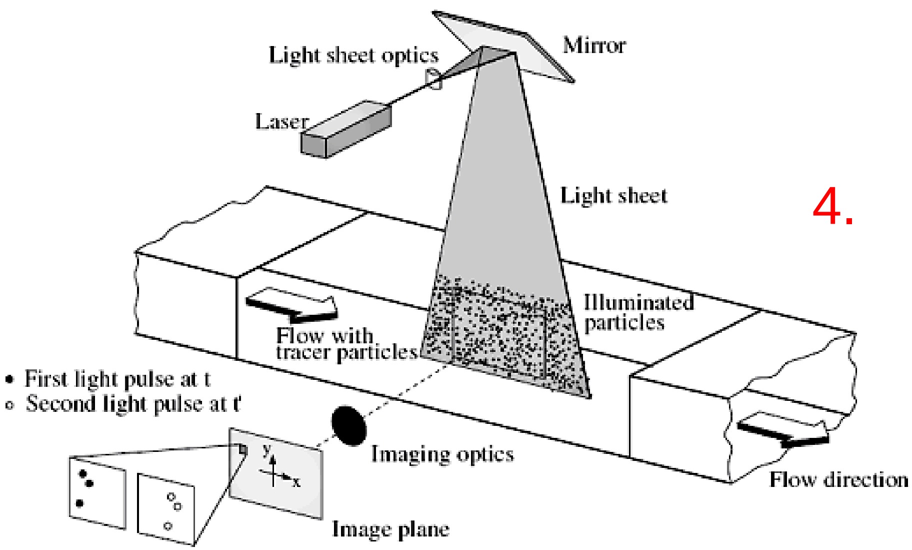
Particle Image Velocimetry (PIV)

1. Flow visualisation by tracer aerosols
   – for flow field detection in general
   – in one flow of two for mixing process

2. Illumination of plane with laser

3. Image recording
   with 1 camera   for 2D flow field
   with 2 cameras for 3D flow field

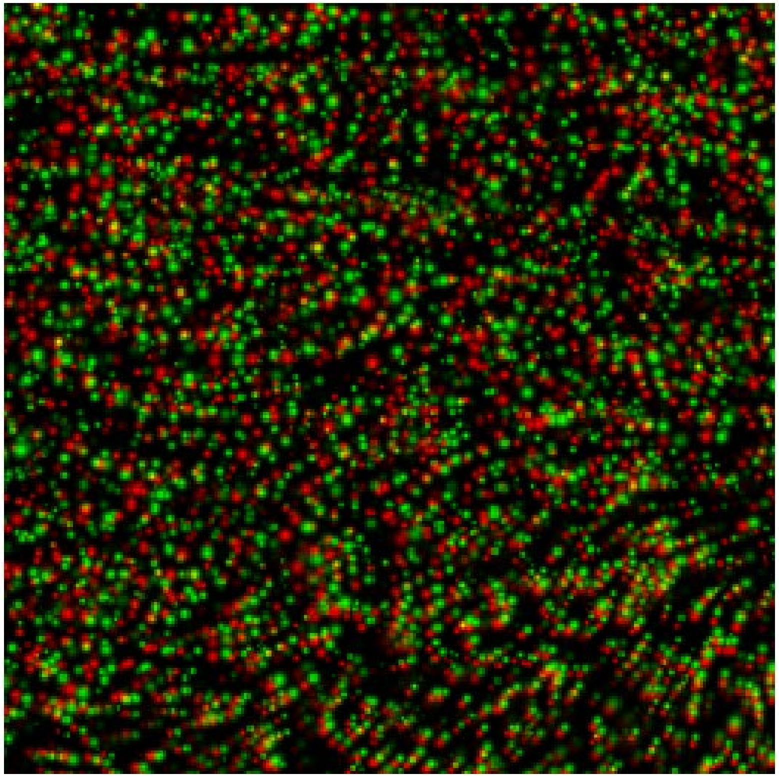
4. Two pictures in a series
   of 20 µs to 2 ms to identify
   – velocity and
   – direction of each tracer
   by statistical data analysis



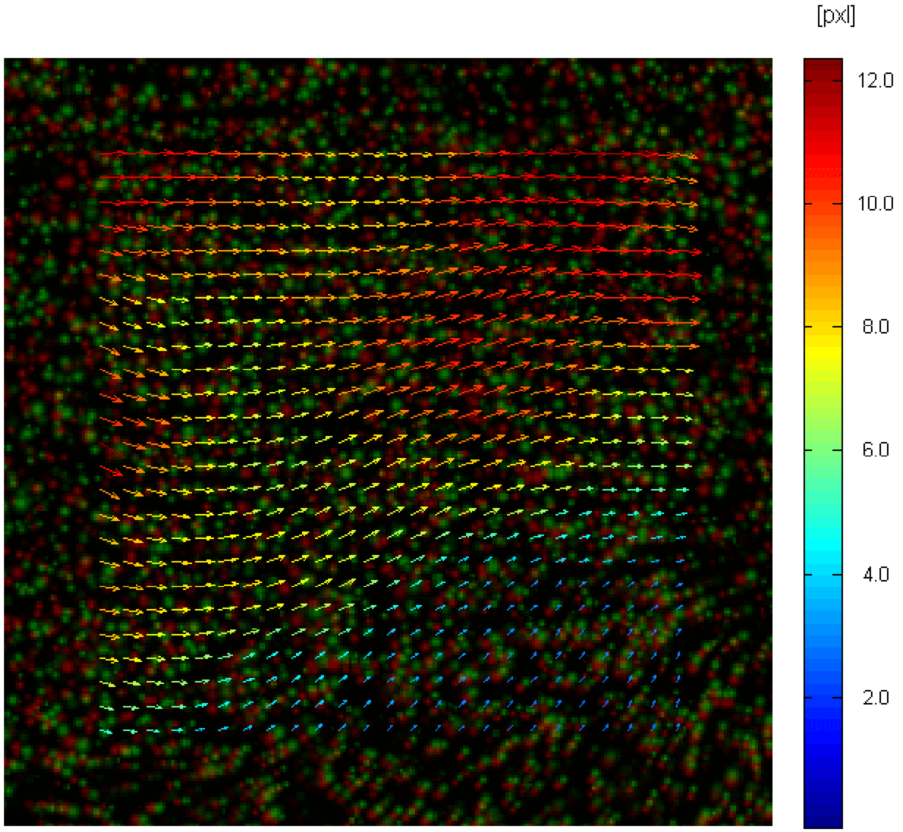
Particle Image Velocimetry (PIV)

Superposition of two images

red: image 1
green: image 2

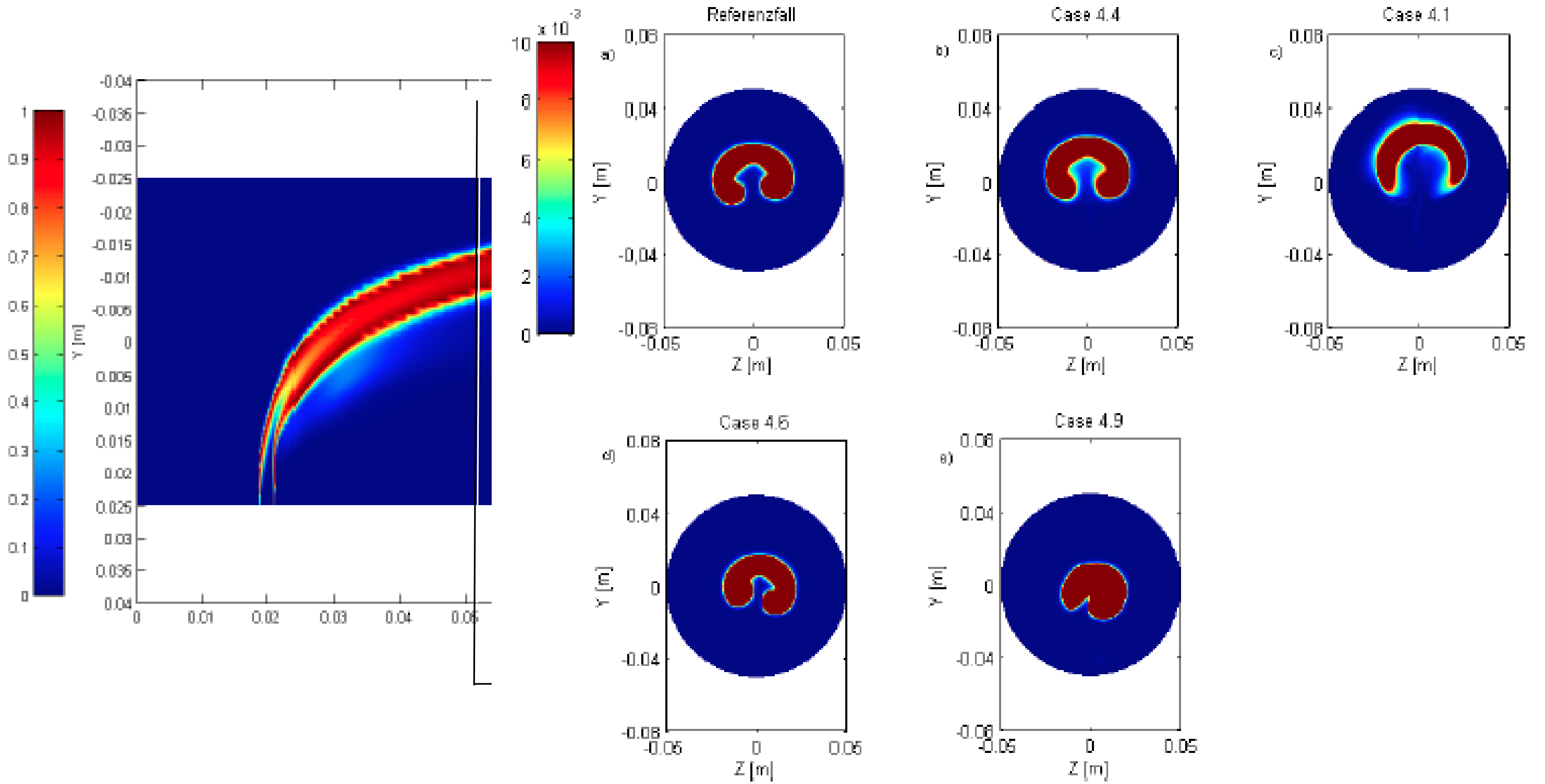


Vector map



Particle Image Velocimetry (PIV) - Example

Mixing Efficiency of Jet In Cross Flow, JICF
Penetration dephts and area for different impuls ratios IR



*ME = Mixing Efficiency: The local mixing quality of two flows is defined as difference between the local tracer concentration and the mean tracer concentration of a fully mixed flow

[Baillifard, M. et al.: 16th EU Conf., Valencia, 2–6 June 2008]

Particle Image Velocimetry (PIV) - Model

Reality → Scaled model for PIV

1. Geometrical similarity
2. Kinematical similarity
2. Dynamical similarity

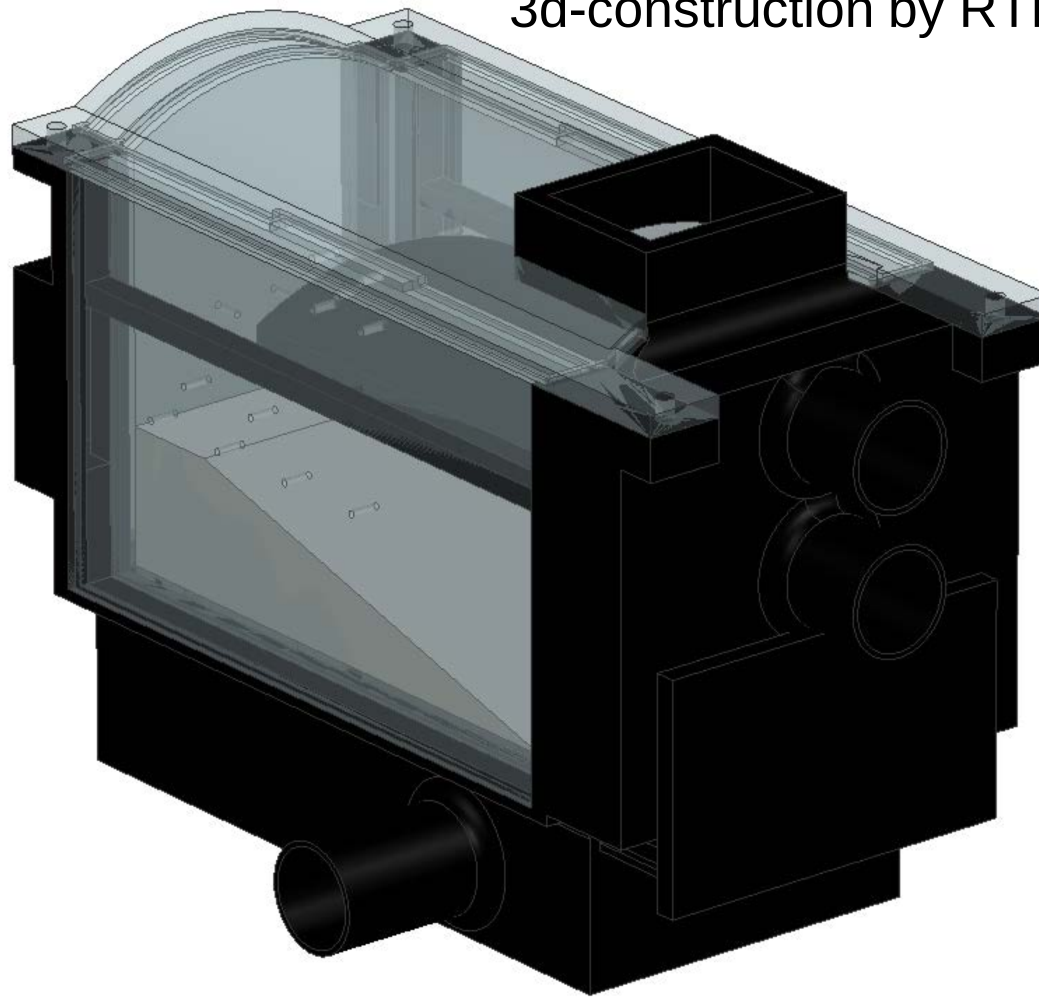
Similarity analysis of dimensionless numbers:

	Reality	Model	Effect
Reynolds Re	26 500	26 700	Turbulence, flow conditions
Schmidt Sc	0.77	0.76	Diffusion
Mach Ma	0.02	0.16	Incompressible fluid < 0.3
Impulse ratio IR x D_{norm}	0.30	0.29	Penetration depth of jet in cross flow (JICF)

Particle Image Velocimetry (PIV) - Model

Reality → Scaled model for 2nd generation PIV: 1:13

3d-construction by RTP

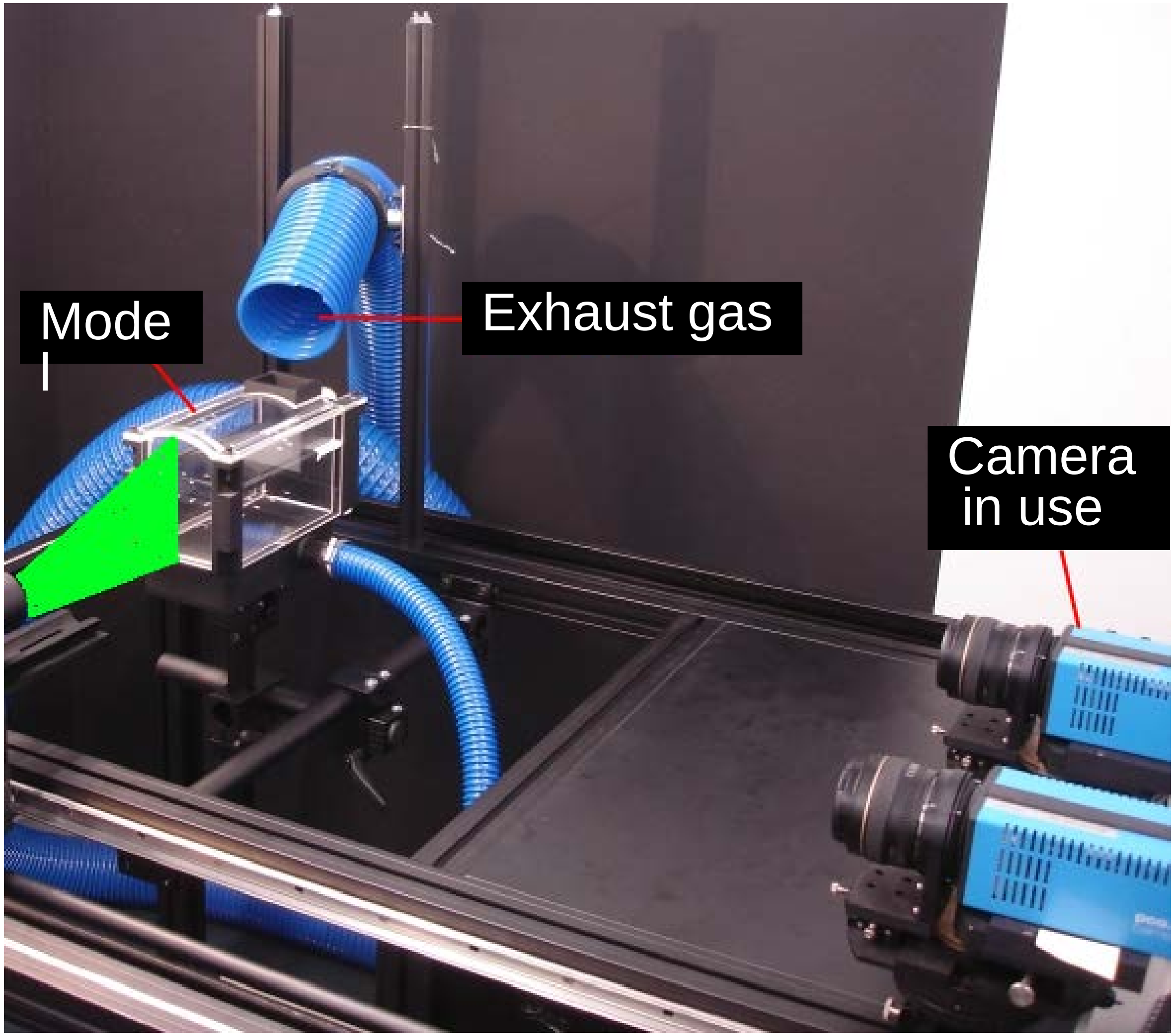


Verenum

Hochschule Luzern
Technik & Architektur

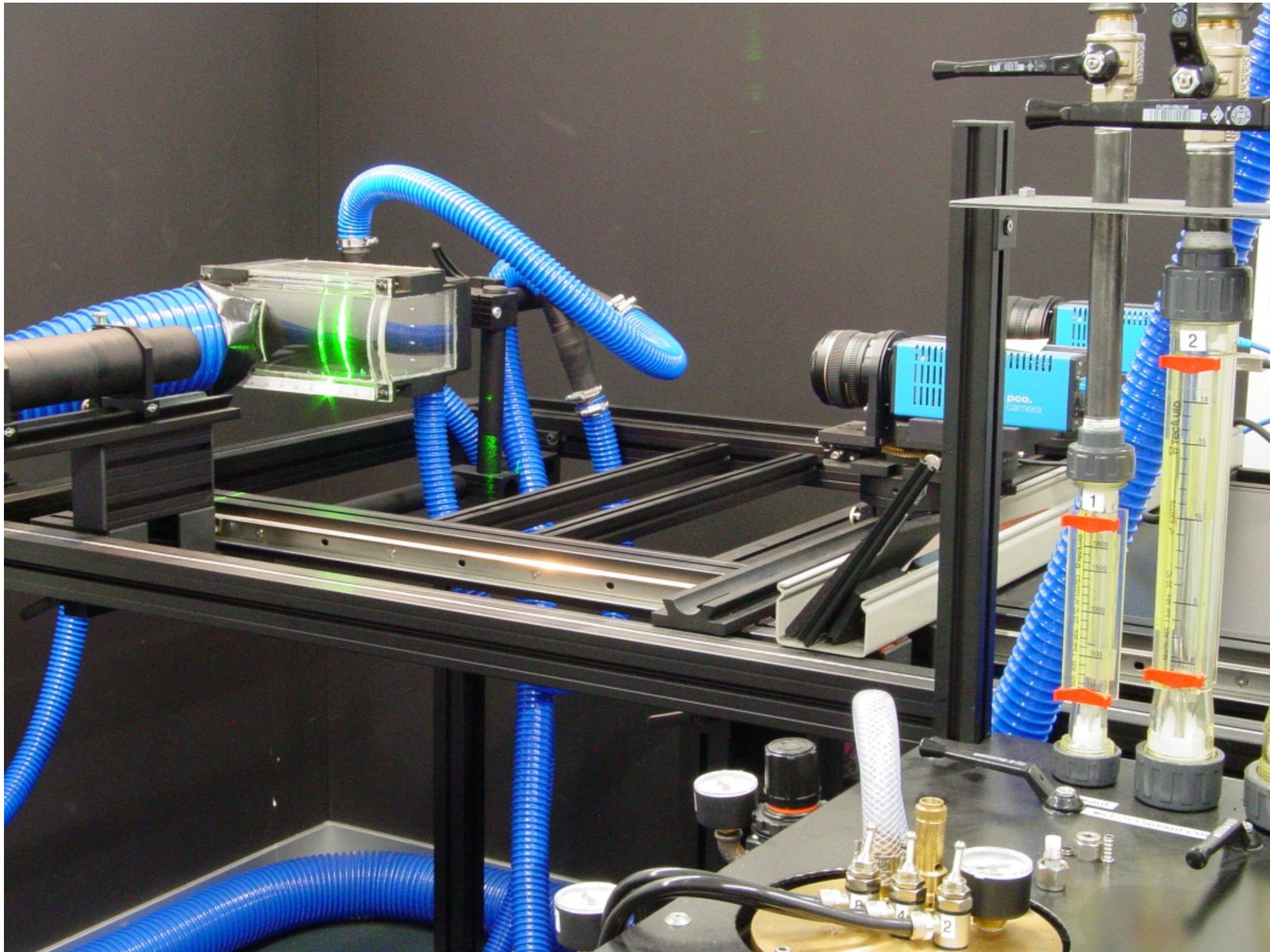
Particle Image Velocimetry (PIV) - Model

Scaled model for 2nd generation PIV: 1:13

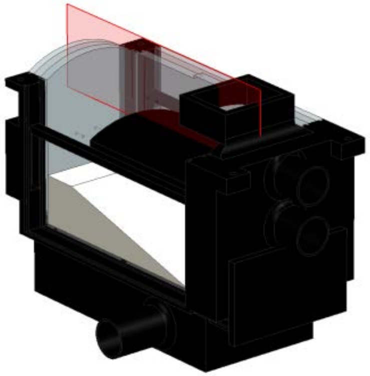


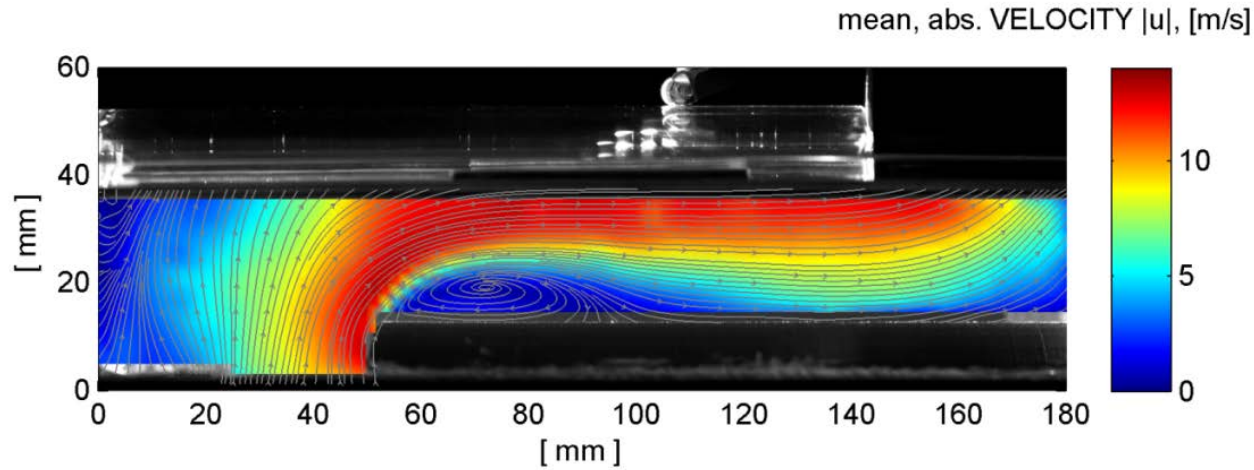
Particle Image Velocimetry (PIV) - Model

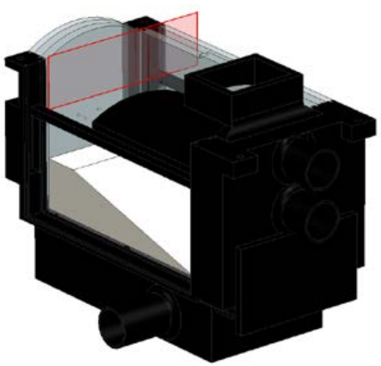
Scaled model for 2nd generation PIV: 1:13

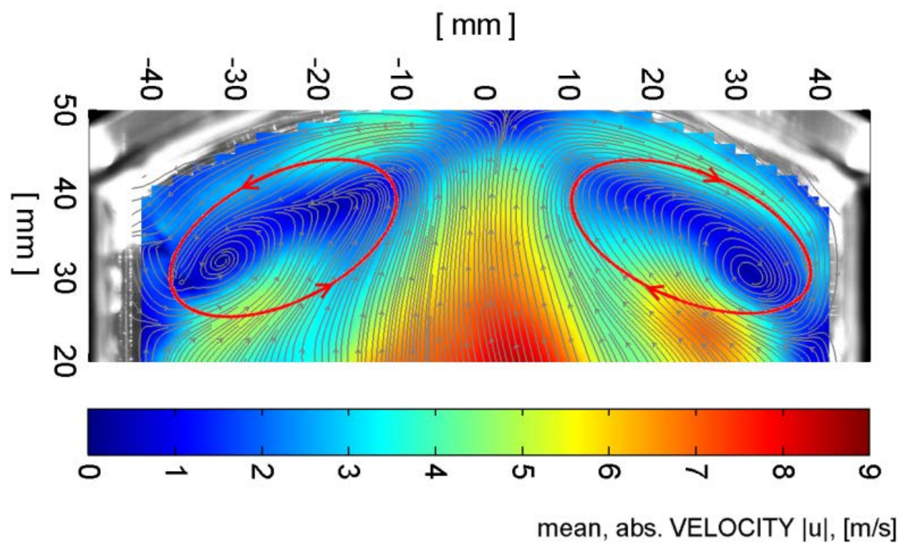


Particle Image Velocimetry (PIV) - Results



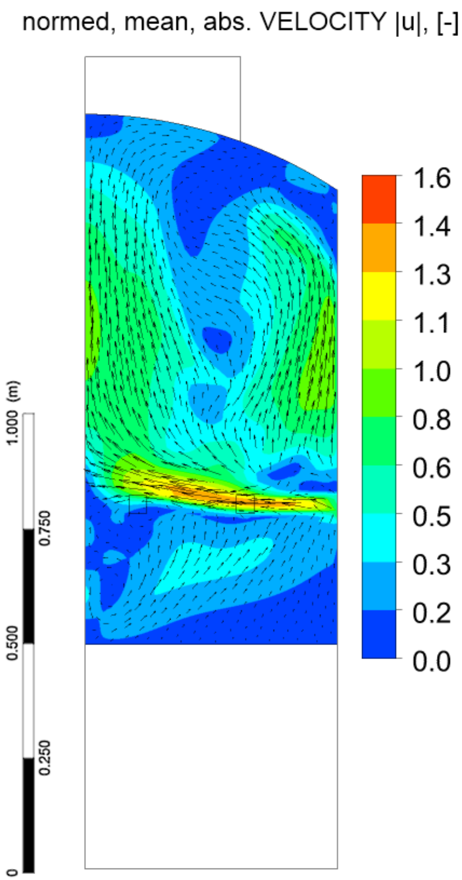




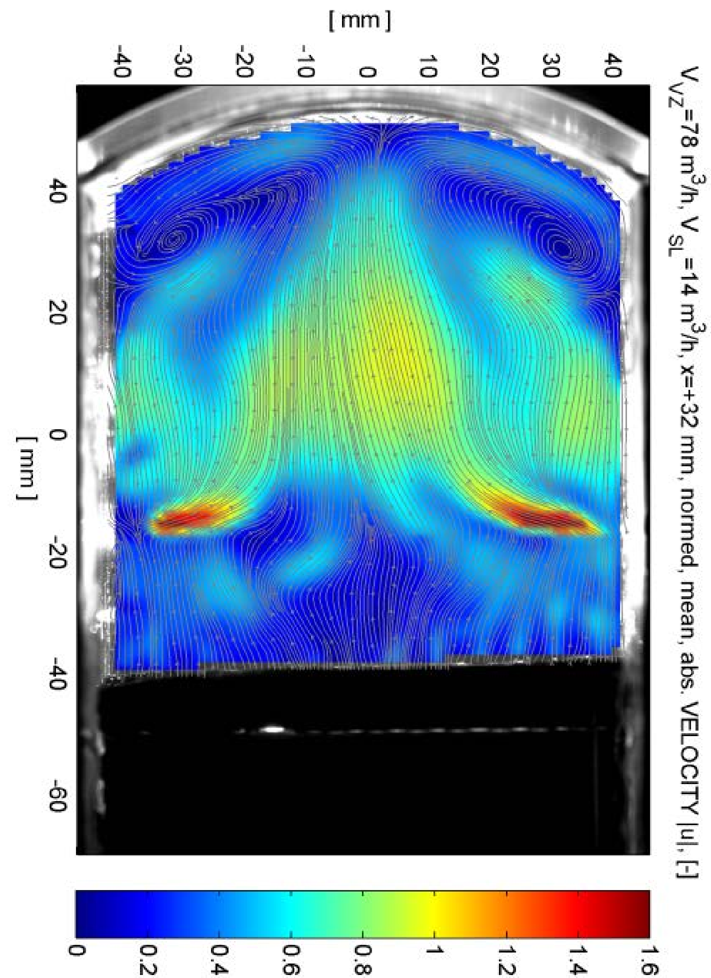


Particle Image Velocimetry (PIV) - Results

CFD

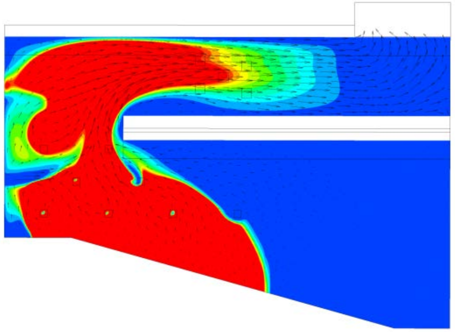


PIV



Verenum

Hochschule Luzern
Technik & Architektur



1. Introduction
2. Target
3. Fluid dynamic optimisation with CFD
4. Comparison with PIV
5. Experiments
6. Conclusions

1.2 MW Moving grate boiler

Operation with ideal grate coverage (80%)

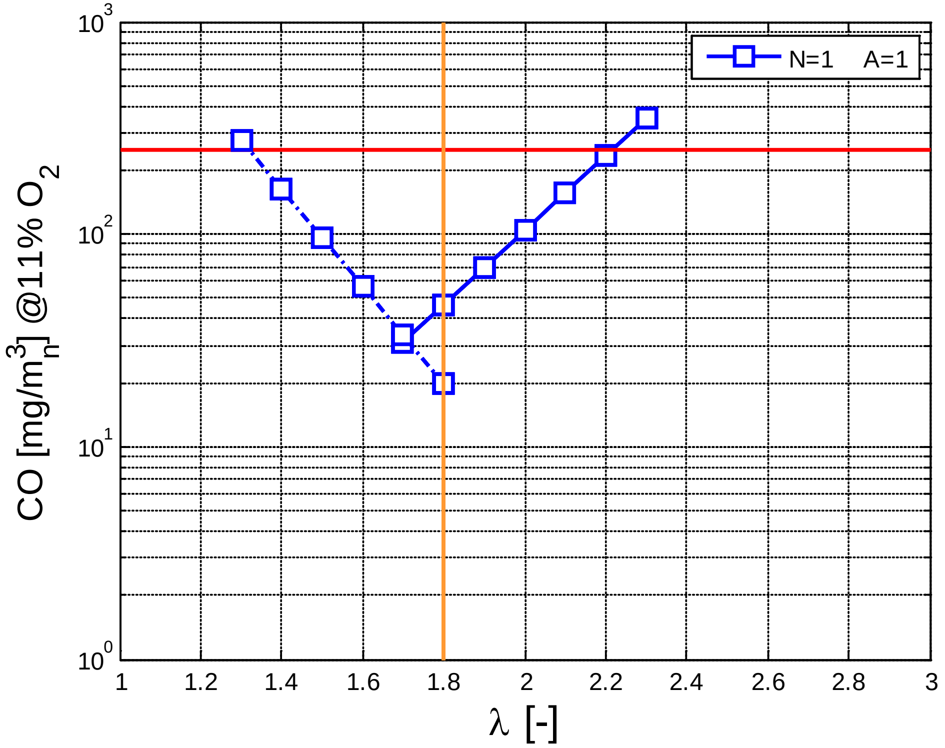
Load ≈ 20%

Verenum

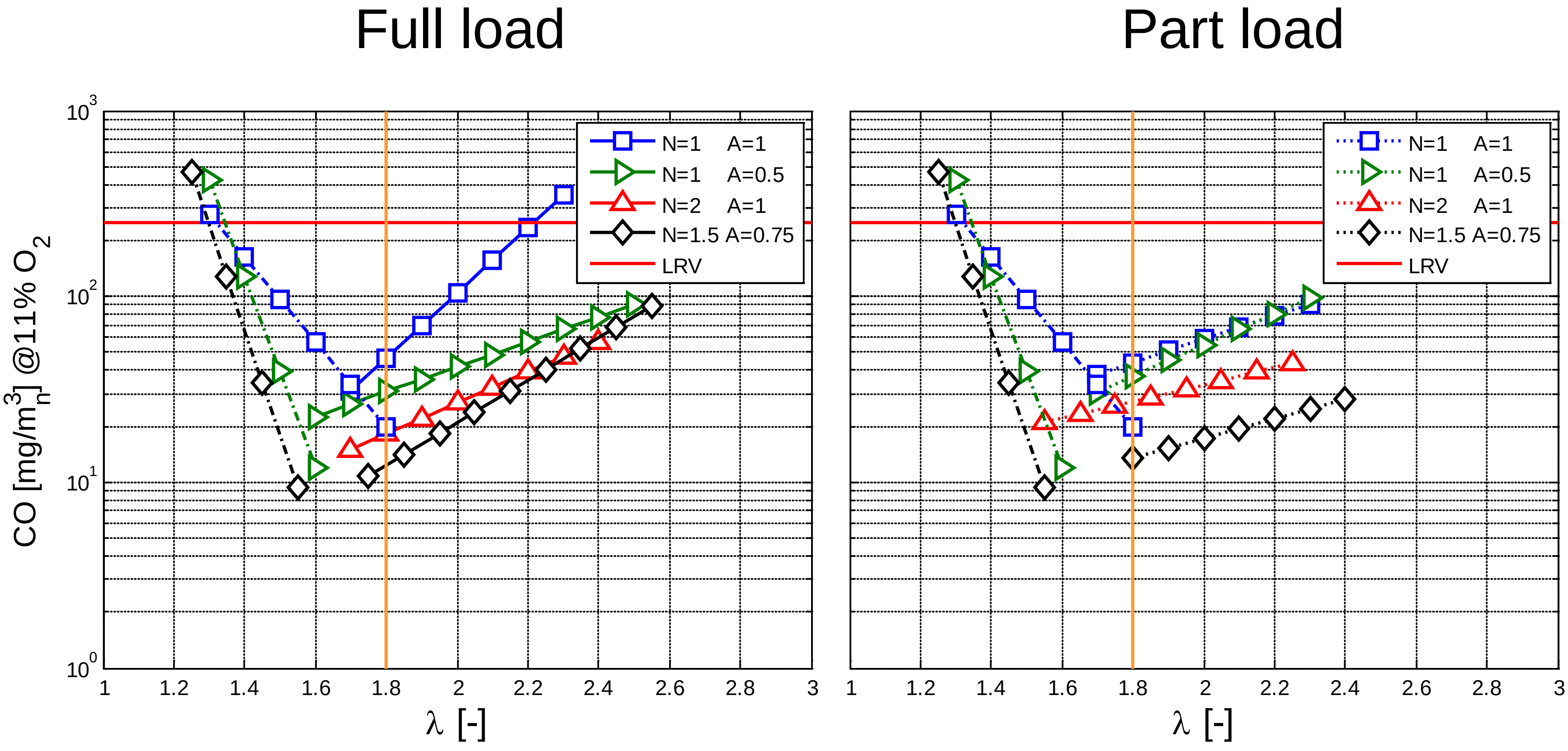
Hochschule Luzern
Technik & Architektur

1. Influence of secondary air injection

Full load



1. Influence of secondary air injection

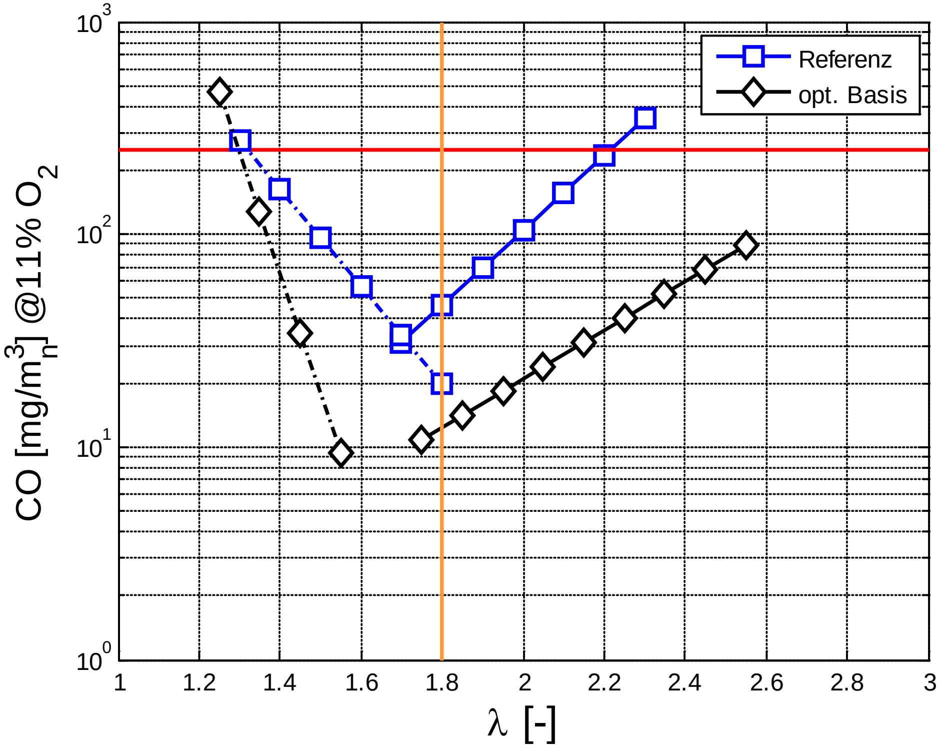


Verenum

Hochschule Luzern
Technik & Architektur

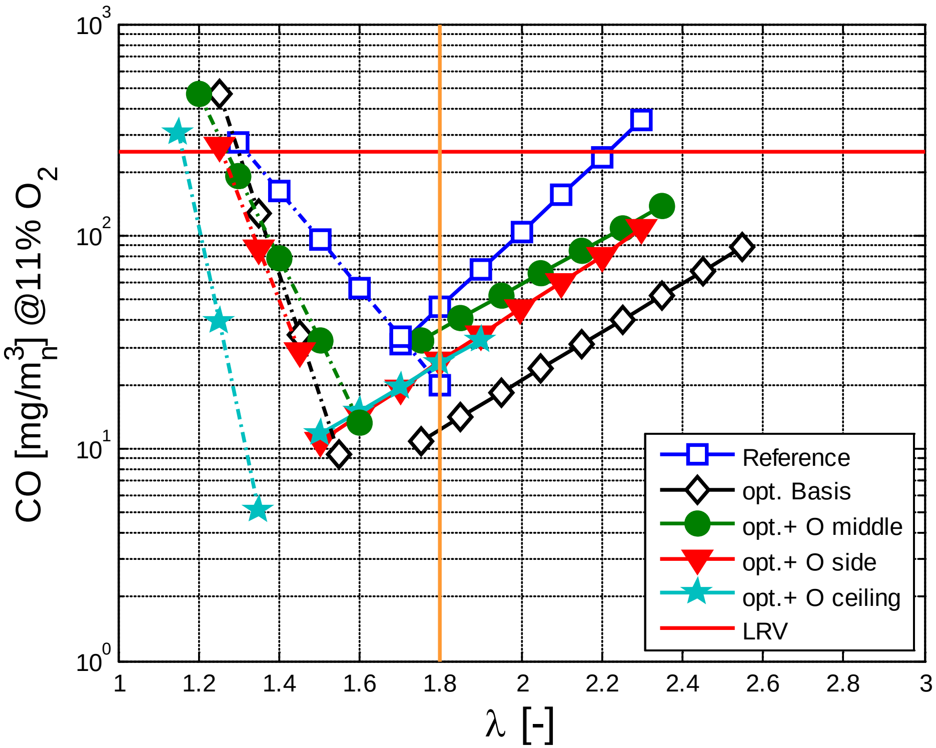
2. Influence of obstacles

Full load



2. Influence of obstacles

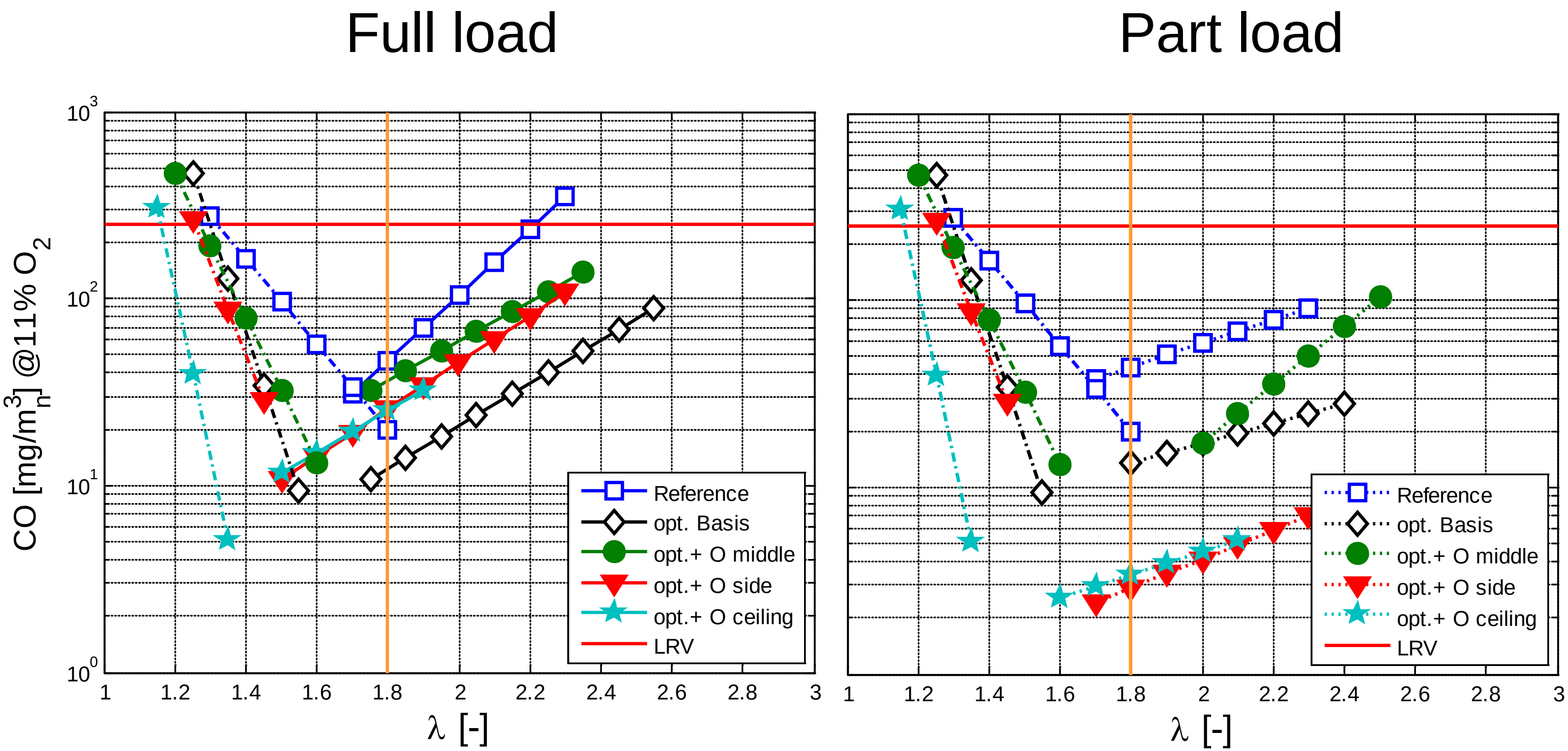
Full load

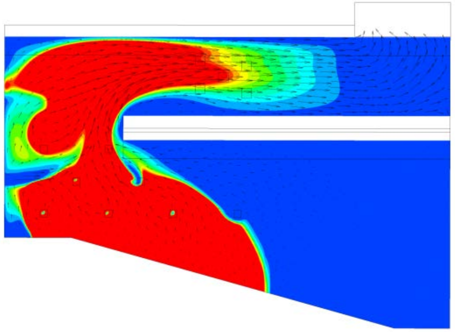


Verenum

Hochschule Luzern
Technik & Architektur

2. Influence of obstacles





1. Introduction
2. Target
3. Fluid dynamic optimisation with CFD
4. Comparison with PIV
5. Experiments
6. Conclusions

1. The CO increase in part load on the investigated grate is not due to reduced turbulence but due to a an incomplete grate coverage. This can be reduced by grate and air control.

2. Optimised secondary air injection reduces CO both in full load and part load by around a factor of 4

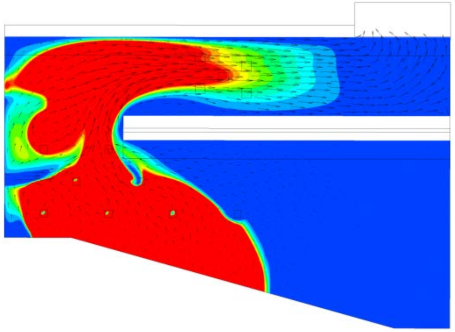
3. By exploiting the optimisation potential, stable operation from < 30% load to full load is achieved with CO < 15 mg/m_n^3 (11% O_2)

4. Simultaneously the optimal excess air ratio is lowered from $\lambda = 1.7$ to $\lambda = 1.5$, which increases the efficiency

5. CFD is powerful to rapidly predict flow optimisation measures.

6. PIV is useful to validate CFD and also to test complex situations on scaled models, however, similarity needs to be considered.

7. The impulse ratio is confirmed to be a key parameter for mixing.



Acknowledgements

Swiss National Science Foundation SNSF

Commission for Technology and Innovation CTI

Schmid AG energy solutions

Verenum

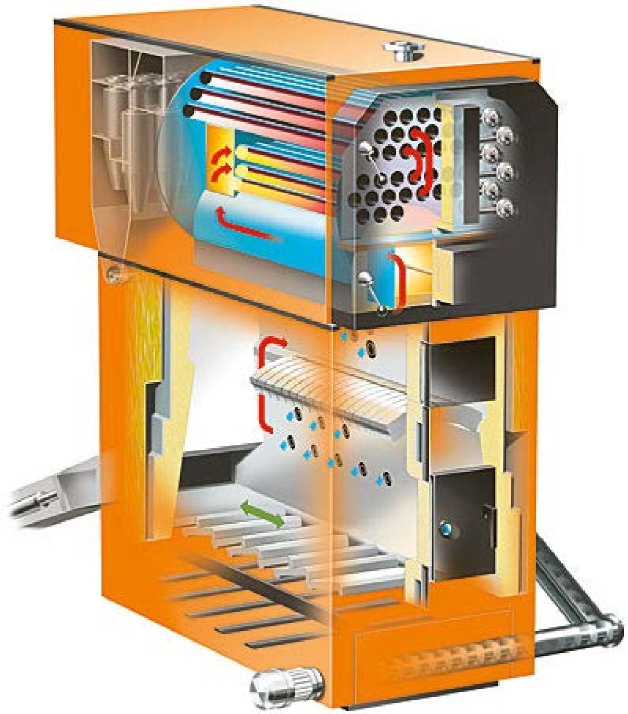
Hochschule Luzern
Technik & Architektur

End of presentation

Particle Image Velocimetry (PIV)

Reality → Scaled model for 1st generation PIV: 1:5

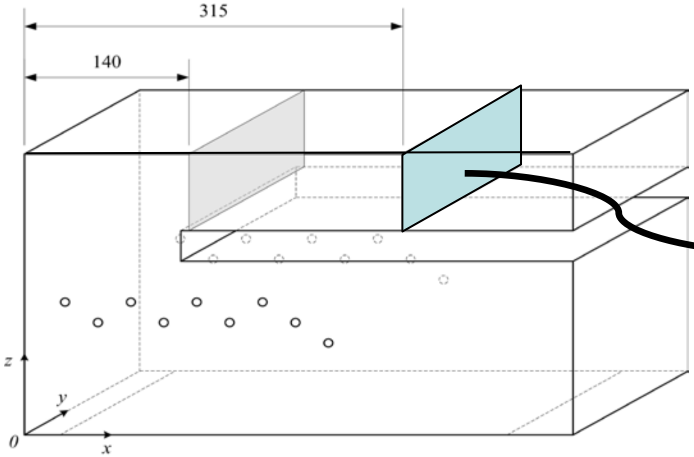
2d-construction ↓



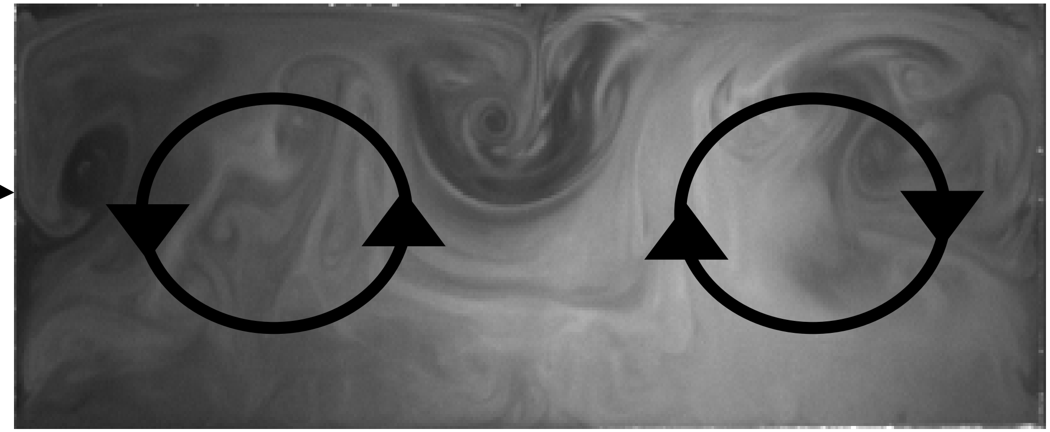
Institute for Fluid Dynamics IFD at ETH Zurich

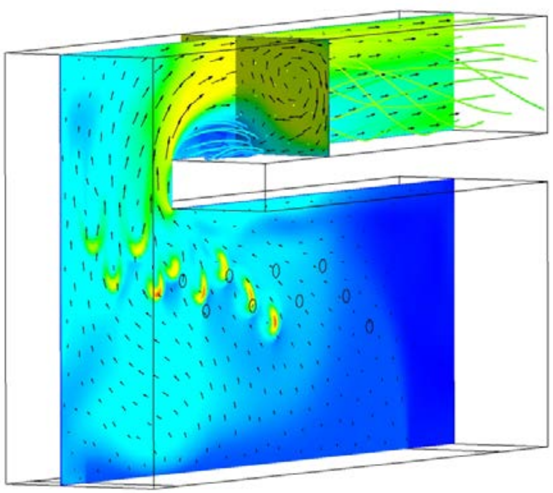
[Baillifard, M. et al.: 16th EU Conf., Valencia, 2–6 June 2008]

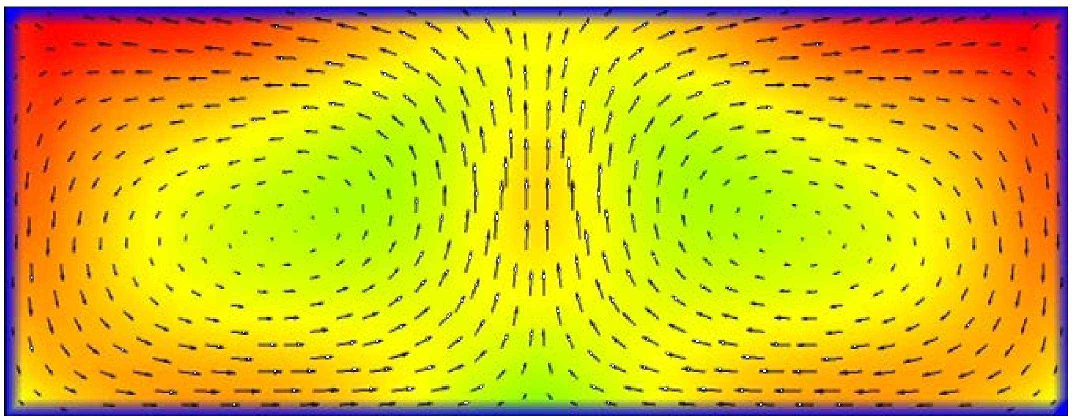
Particle Image Velocimetry (PIV)



Scaled model for 1st generation PIV: 1:5

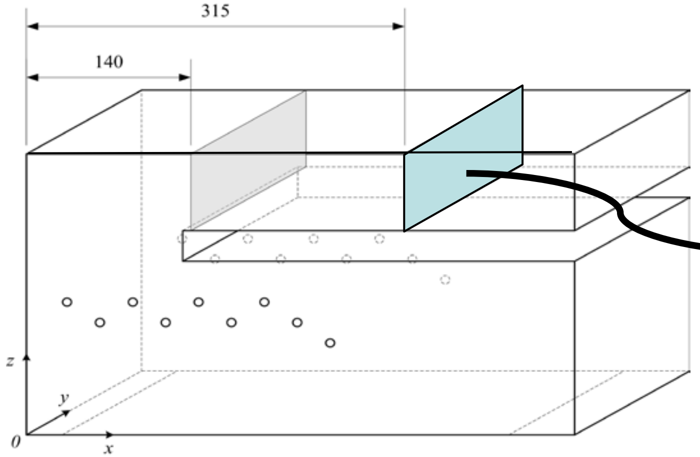




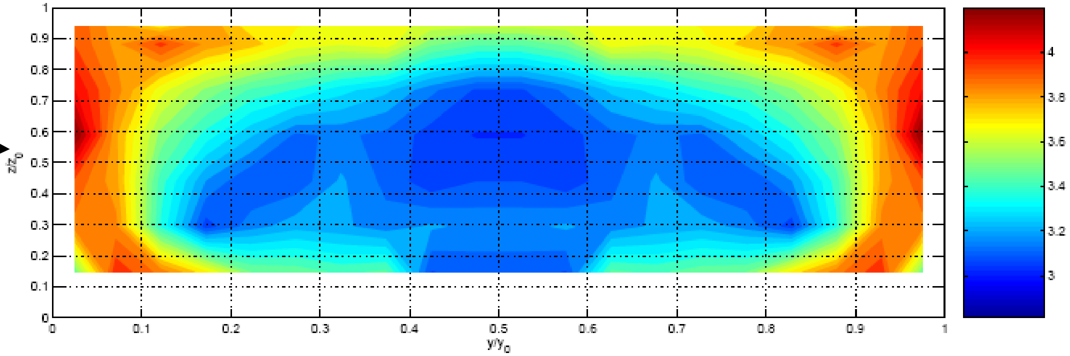


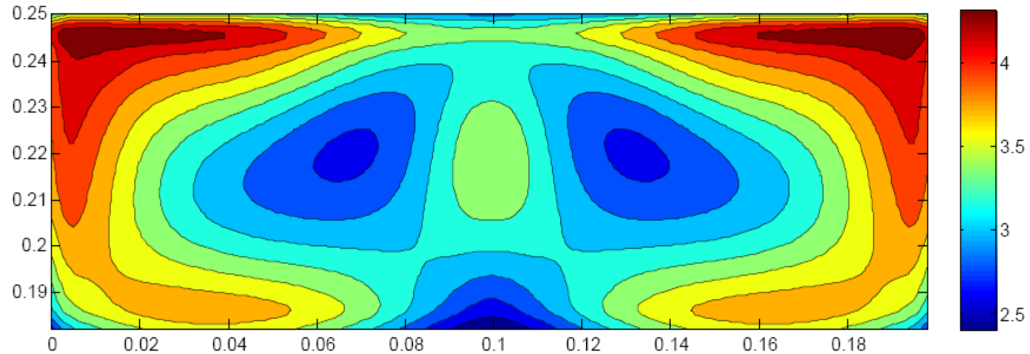
CFD

Particle Image Velocimetry (PIV)



Scaled model for 1st generation PIV: 1:5





CFD

[Baillifard, M. et al.: 16th EU Conf., Valencia, 2–6 June 2008]

Verenum

Hochschule Luzern
Technik & Architektur

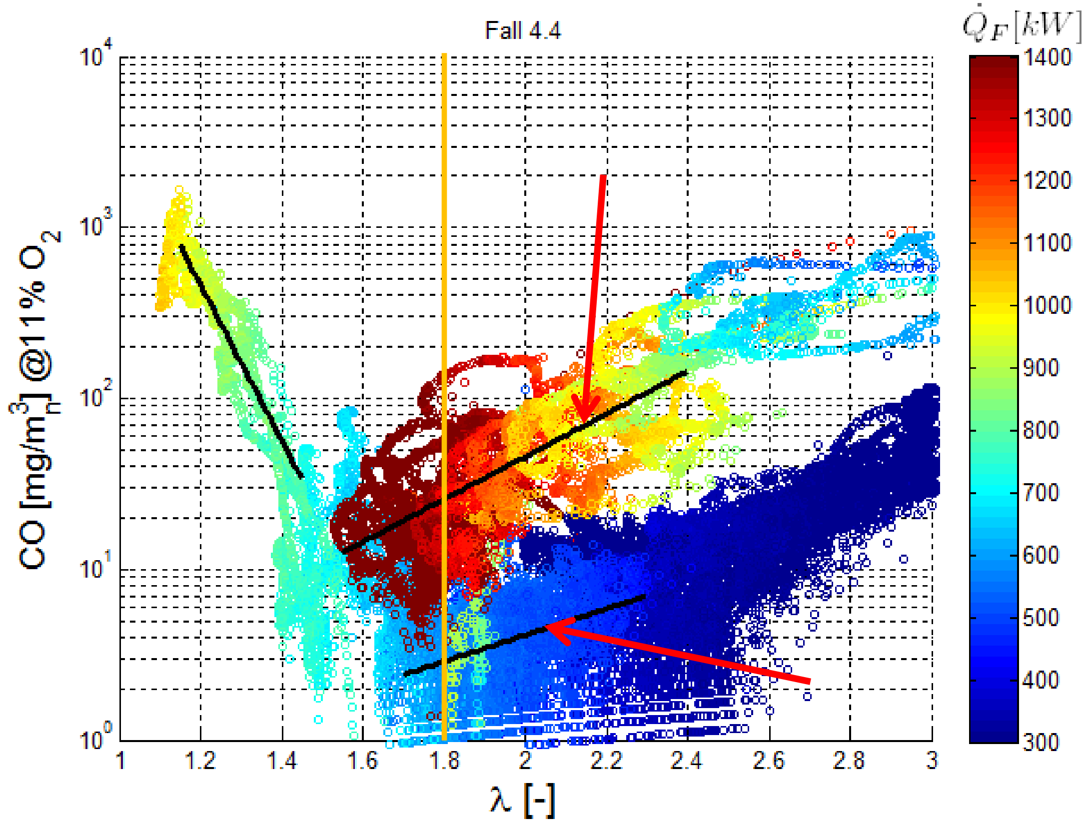
Interpretation

- Stationary phase with similar conditions:
  - PA/PA_{Ref}
  - PA/SA_1
  - SA_1/SA_2

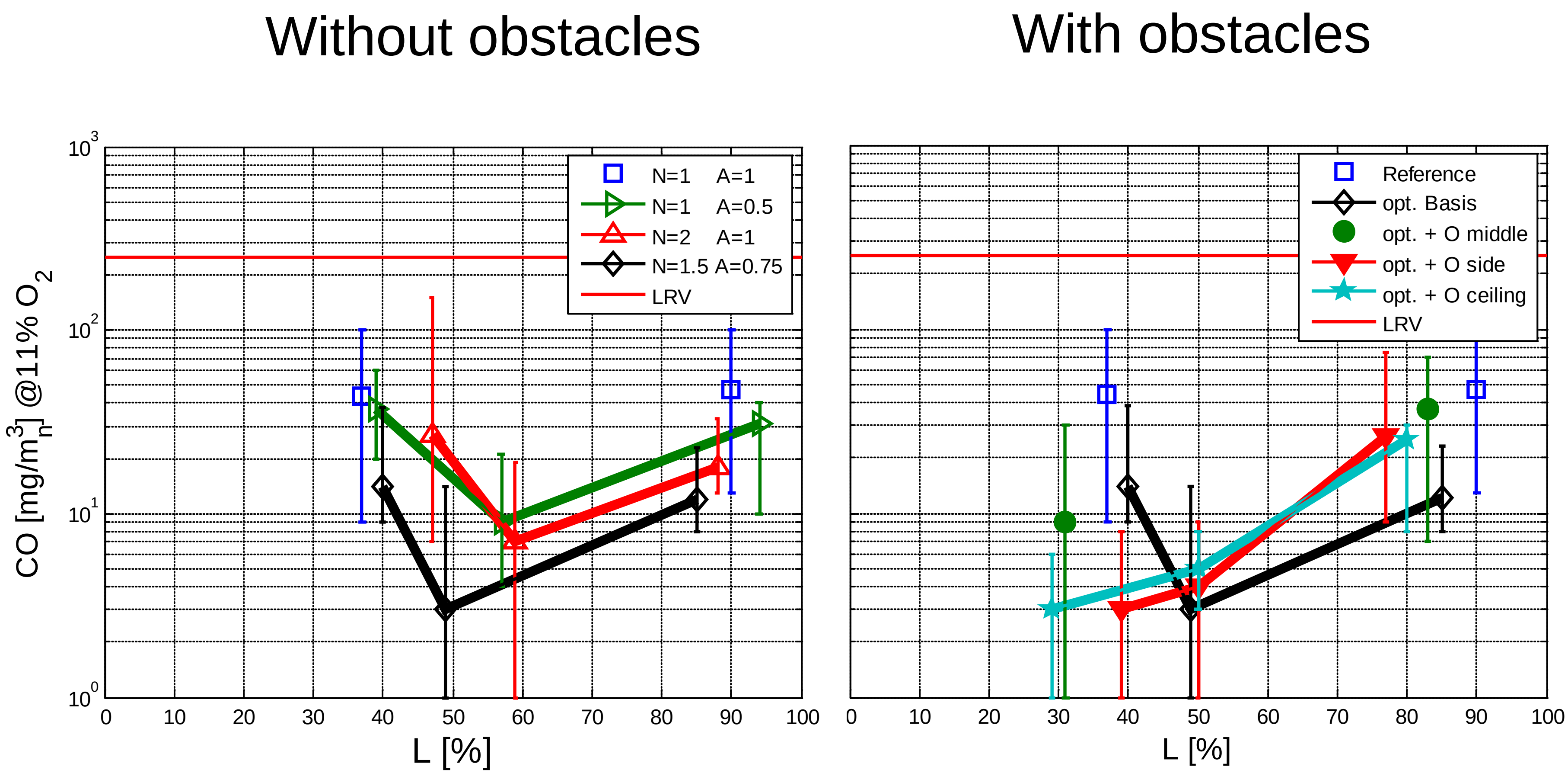
- Comparison of the cases in part and full load :

  1. CO/Lambda-Diagram are approximated logarithmically

  2. CO-value at $\lambda_{tot} = 1.8$ as reference value



3. CO at λ=1.8 as function of the load



Verenum

Hochschule Luzern
Technik & Architektur

Ideal grate coverage of 90% at 15% load

Verenum

Hochschule Luzern
Technik & Architektur

Non-ideal grate coverage at 40% load with uncovered sections at the end

Measurements

- Gas composition (O_2, CO_2, CO)
- Flue gas volume flow (Δp with pitot tube)
- Combustion air volume flows PA_1, PA_2, SA_1, SA_2 (heated wire anometry)
- Combustion temperature (PT100 in ceramic tube)
- Flue gas temperature (thermoelement)

- Excess air ratio
- Thermal firing capacity