Identification of coherent structures in horizontal slug flow

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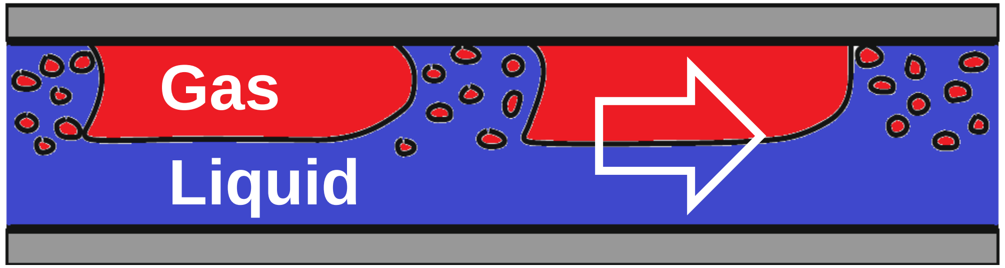
What is slug flow?

Slug flow (in horizontal pipes):

- gas-liquid flow pattern
- continuous liquid phase
- intermittent sequence of liquid slugs
- followed by longer gas bubbles



Problems of slug flow:

- large uncertainty in flow measurement
- large pressure fluctuations & loss
- damage of piping

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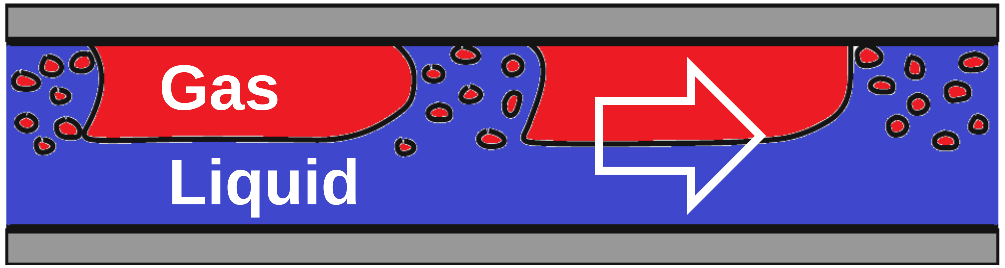

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WANT **characterization of liquid slugs in time and space**

IDEA **liquid slugs are statistically similar in time and space (⇨ coherent structure)**

Snapshot Proper Orthogonal Decomposition

Decomposition of the flow parameter field (Sirovich, 1987):

$$f(x,t) = \bar{f}(x) + f'(x,t) = \bar{f}(x) + \sum_j \boxed{a_j(t)}\,\boxed{\phi_j(x)}$$

time-averaged field

temp. fluctuations

spatial modes

temp. coefficients

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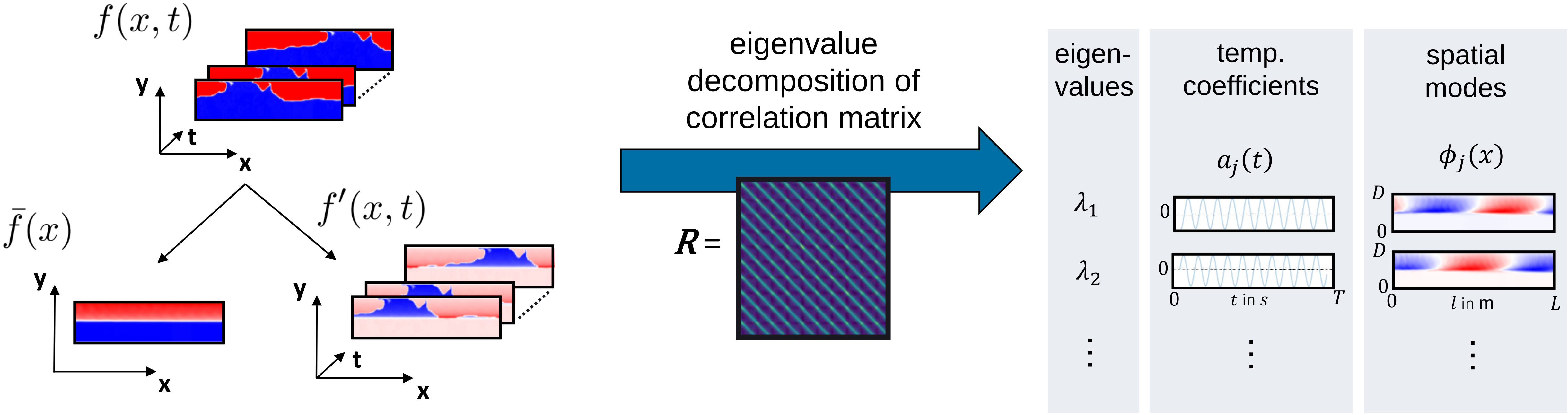


eigenvalue decomposition of correlation matrix

eigen-values

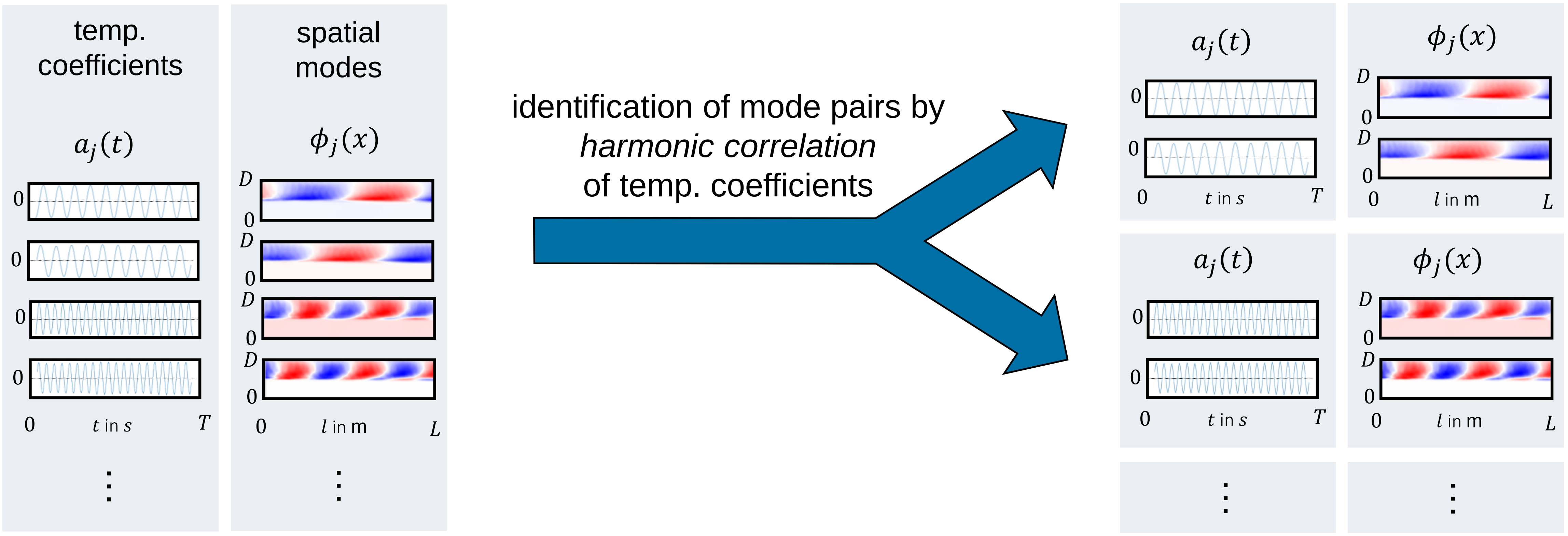
temp. coefficients

spatial modes

Mode coupling

- dynamics of coherent structure can be described by mode pair (Sieber et al., 2016)
- parameters of identified mode pair:
    - ➢ combined energy content E (in terms of a discrete time signal)
    - ➢ dominant frequency f

Identified mode pairs



identification of mode pairs by *harmonic correlation* of temp. coefficients

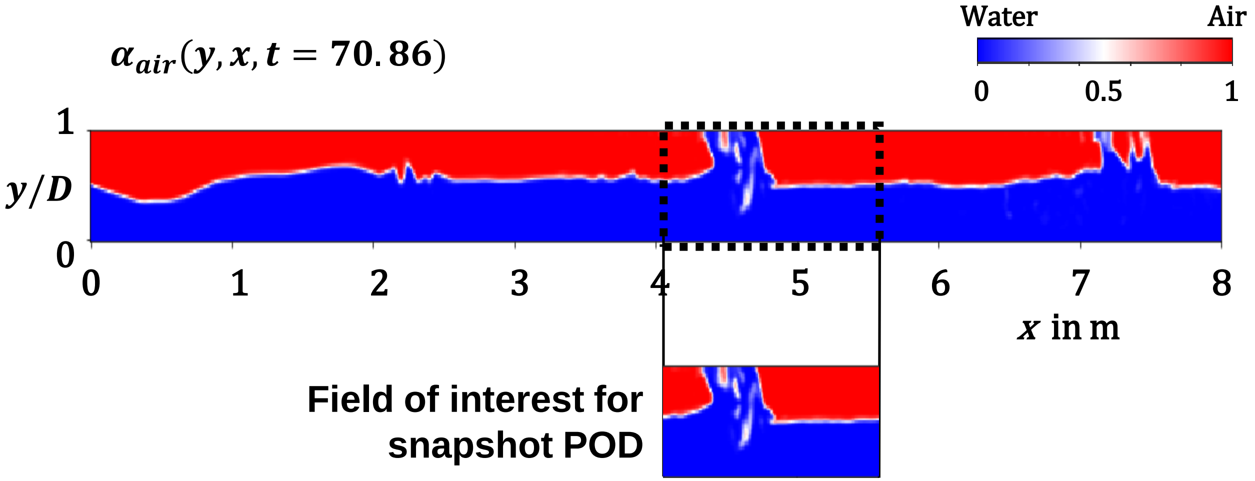
Slug flows for analysis

CFD-Simulation of a periodic air-water slug flow

(slugging frequency $1\ \mathrm{Hz}$)

- time-invariant periodic perturbation of vertical position of interface at inlet (Frank, 2008)
  → slug formation of $1\ \frac{slug}{second} = \mathbf{1\ Hz}$
- validation of slug characterization with snapshot POD

Gas volume fraction field α_{air}



Field of interest for snapshot POD

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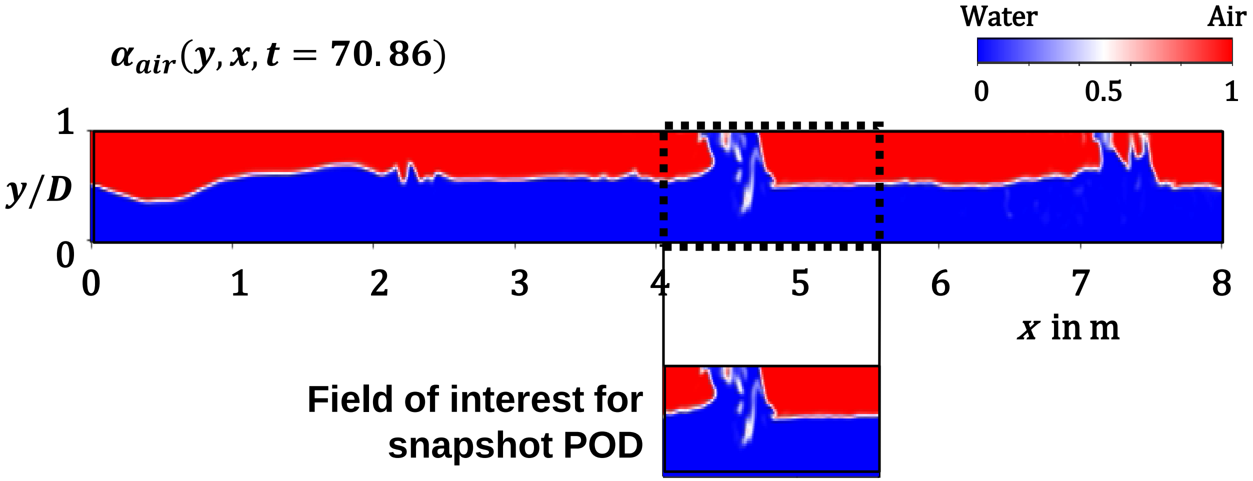

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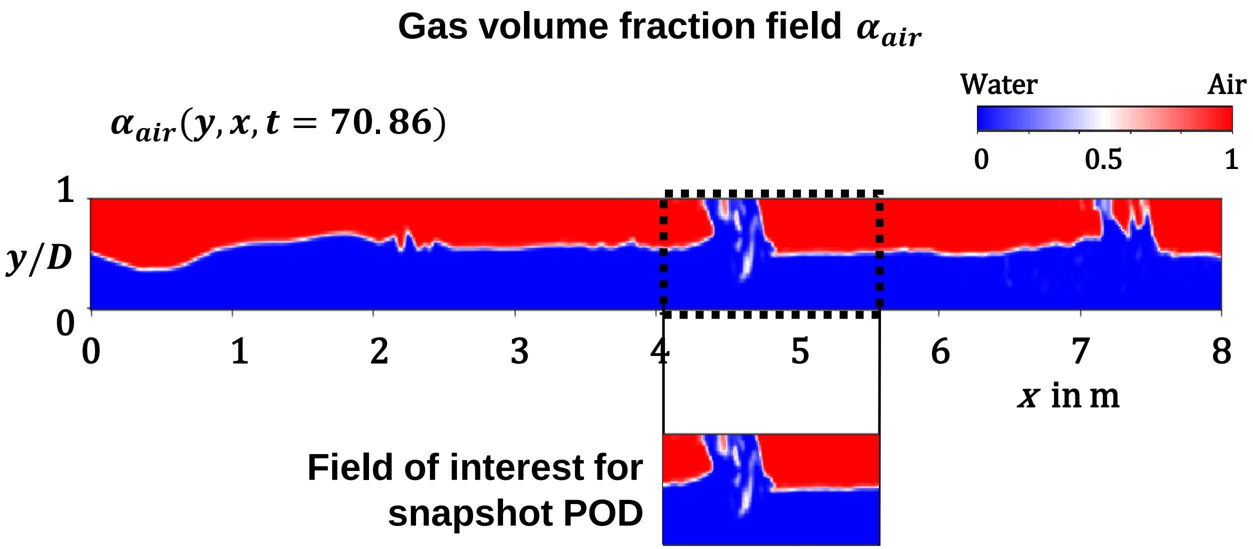
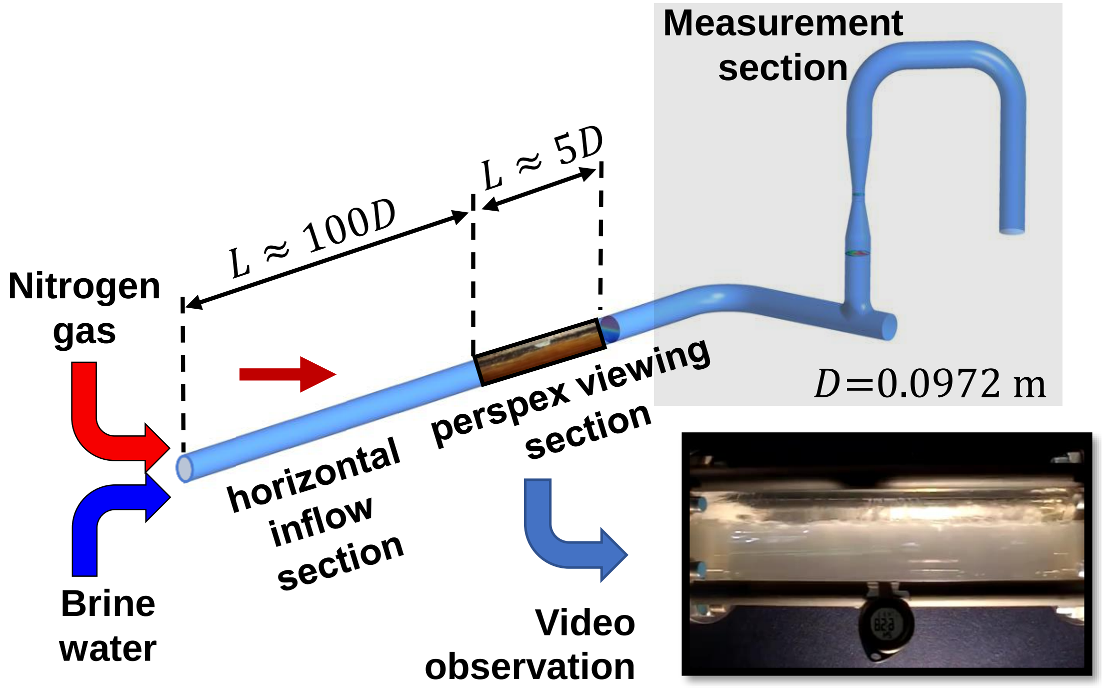


Video observations of a nitrogen - brine water slug flow

(avg. slugging frequency $1.4\ \mathrm{Hz}$)

- performed by TUV SUD NEL (JRP Report ENG58, 2018)
- counted slugs: $\frac{72\ slug}{50\ second} \approx \mathbf{1.4\ Hz}$



Slug flows for analysis

CFD-Simulation of a periodic air-water slug flow

(slugging frequency 1 Hz)

Video observations of a nitrogen - brine water slug flow

(avg. slugging frequency 1.4 Hz**)**

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UD NEL (JRP Report

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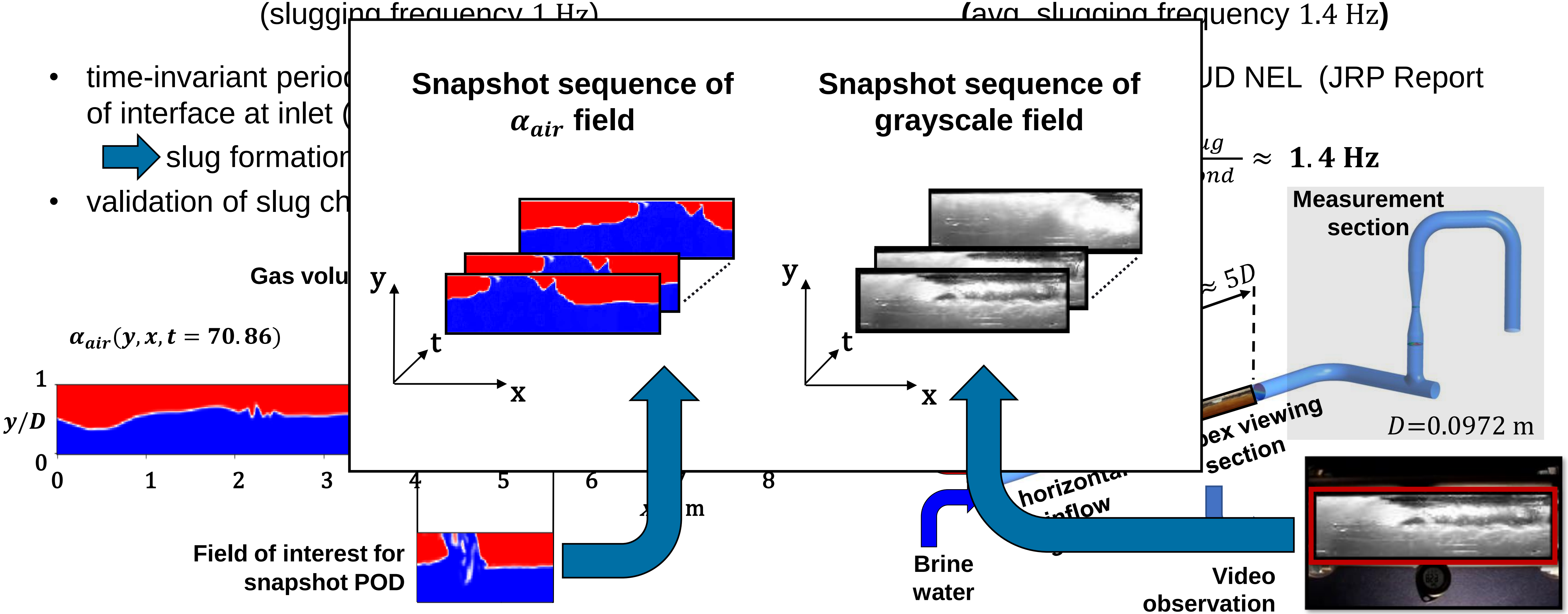
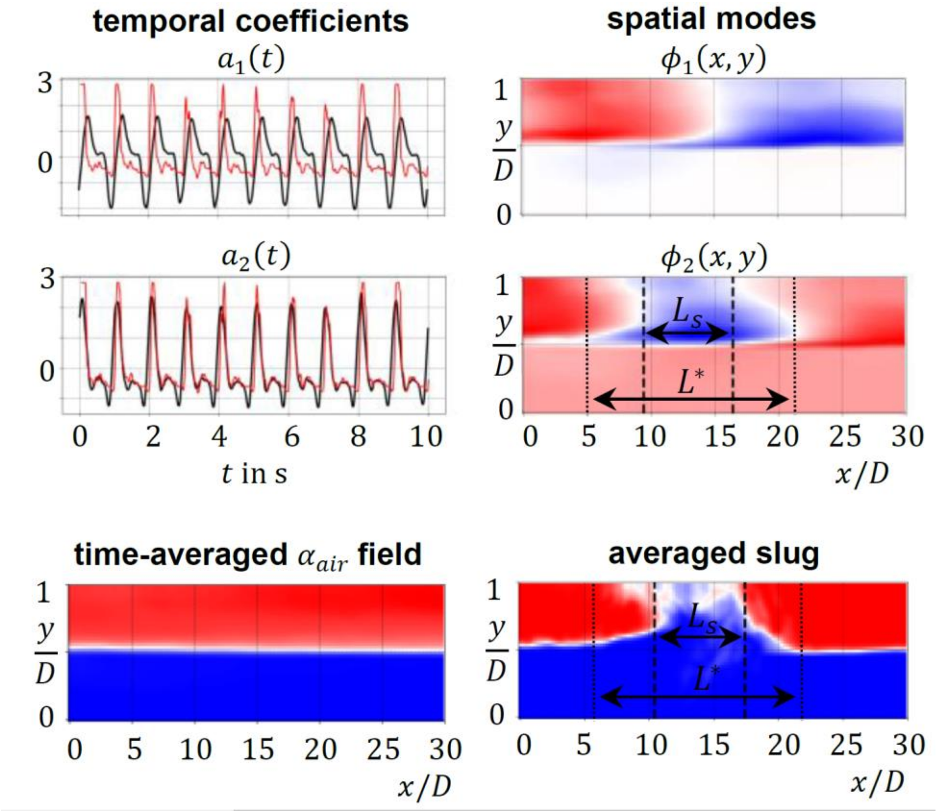


Results

CFD data


temporal coefficients

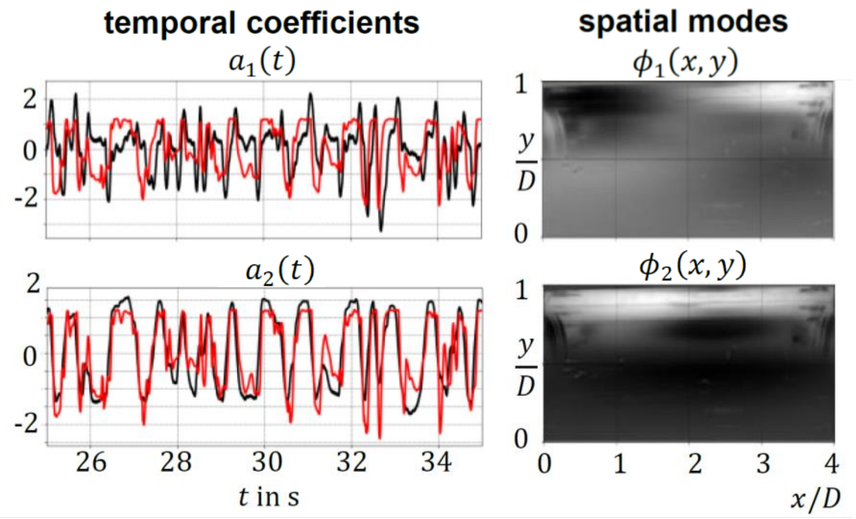
spatial modes

time-averaged α_{air} field

averaged slug

▬ temp. coef.
▬ liquid level

Experimental data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Characterization of slugging structures:

	CFD	Experiment
Energy content E of mode pair (ϕ_1, ϕ_2)	$46.6\ \%$	$55.9\ \%$
Dominant Frequency f of mode pair (ϕ_1, ϕ_2)	1 Hz	1.4 Hz
Averaged slug body length L_s	$7\ D$	> 4D
Averaged structure length L^*	$16\ D$	7.6 D

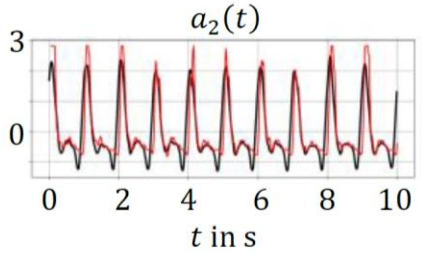
Summary, conclusion and outlook

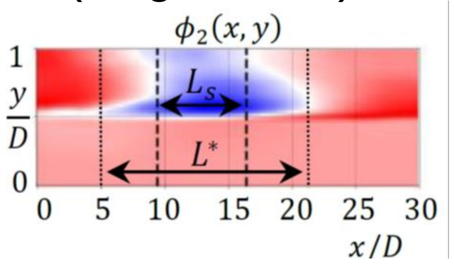
Summary:

- **quantification of slugging structures with snapshot POD in:**

  - **time** **&** **space**

(dynamics, frequency) (length scale)





Conclusion:

- **snapshot POD is a valid tool for characterisation of the slugging structures.**

Outlook:

- **quantify experimental slug flow (performed during MultiFlowMet I & II)**
- **find relation between slugging structures and uncertainties**

Thank you very much for your attention.

Acknowledgements

This work was supported through the Joint Research Project “Multiphase flow reference metrology”. This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme. The authors would like to thank Terri Leonard and Marc MacDonald from TUV SUD NEL, who provided the experimental video observations.

EMPIR EURAMET

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Status: 06/19

APPENDIX - CFD-Simulation

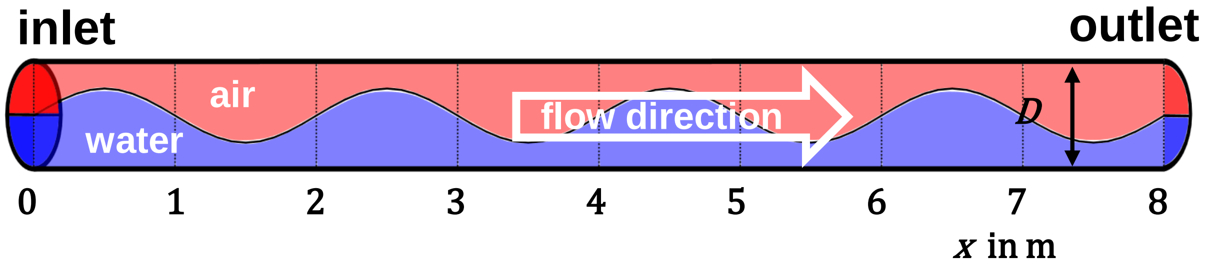
Set up:

- Air-water slug flow adopted from (Frank, 2008)
- straight horizontal pipe $(L = 8m,\ D = 0.05m)$
- unsteady RANS approach
  (k-ω-SST, Ansys Fluent)
- time-invariant perturbation of interface at inlet
  ➡ slug formation of $1\ \frac{slug}{second} = 1\ \mathrm{Hz}$

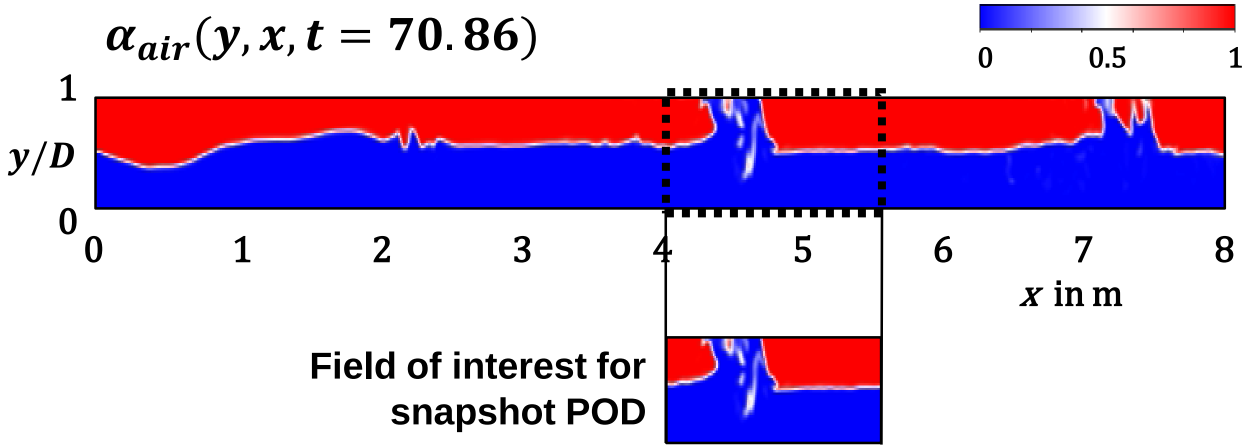
- flow parameters and superficial velocities:

	water	air
density in $\frac{\mathrm{kg}}{\mathrm{m}^3}$	998.2	1.225
dyn. viscosity in $\mathrm{Pa \cdot s}$	$1.003 \cdot 10^{-3}$	$1.789 \cdot 10^{-5}$
superficial vel. in $\frac{\mathrm{m}}{\mathrm{s}}$	1.0	1.0

Initial field



Gas volume fraction field α_{air}


$\boldsymbol{\alpha_{air}(y, x, t = 70.86)}$

Field of interest for snapshot POD

- $\alpha_{air}(x, y, t)$ acquired for $t\ \in [70s, 80s]$ at $100\ \mathrm{Hz}$

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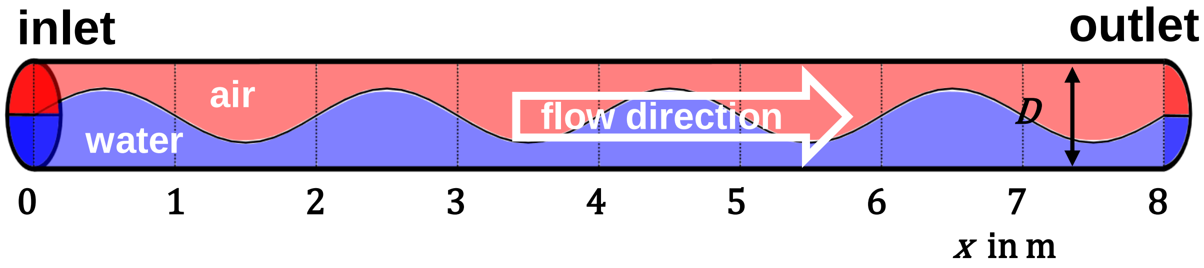

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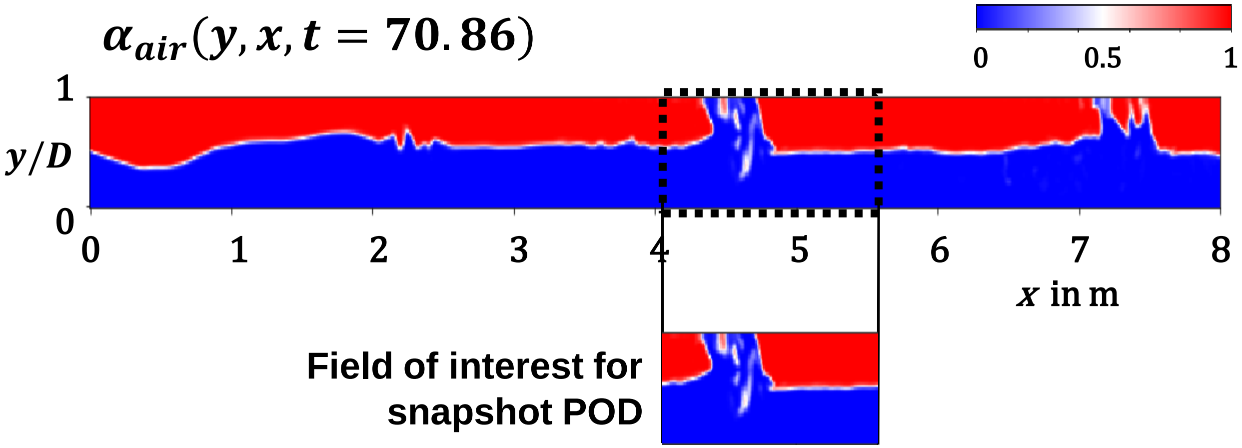

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APPENDIX - Experimental video observations

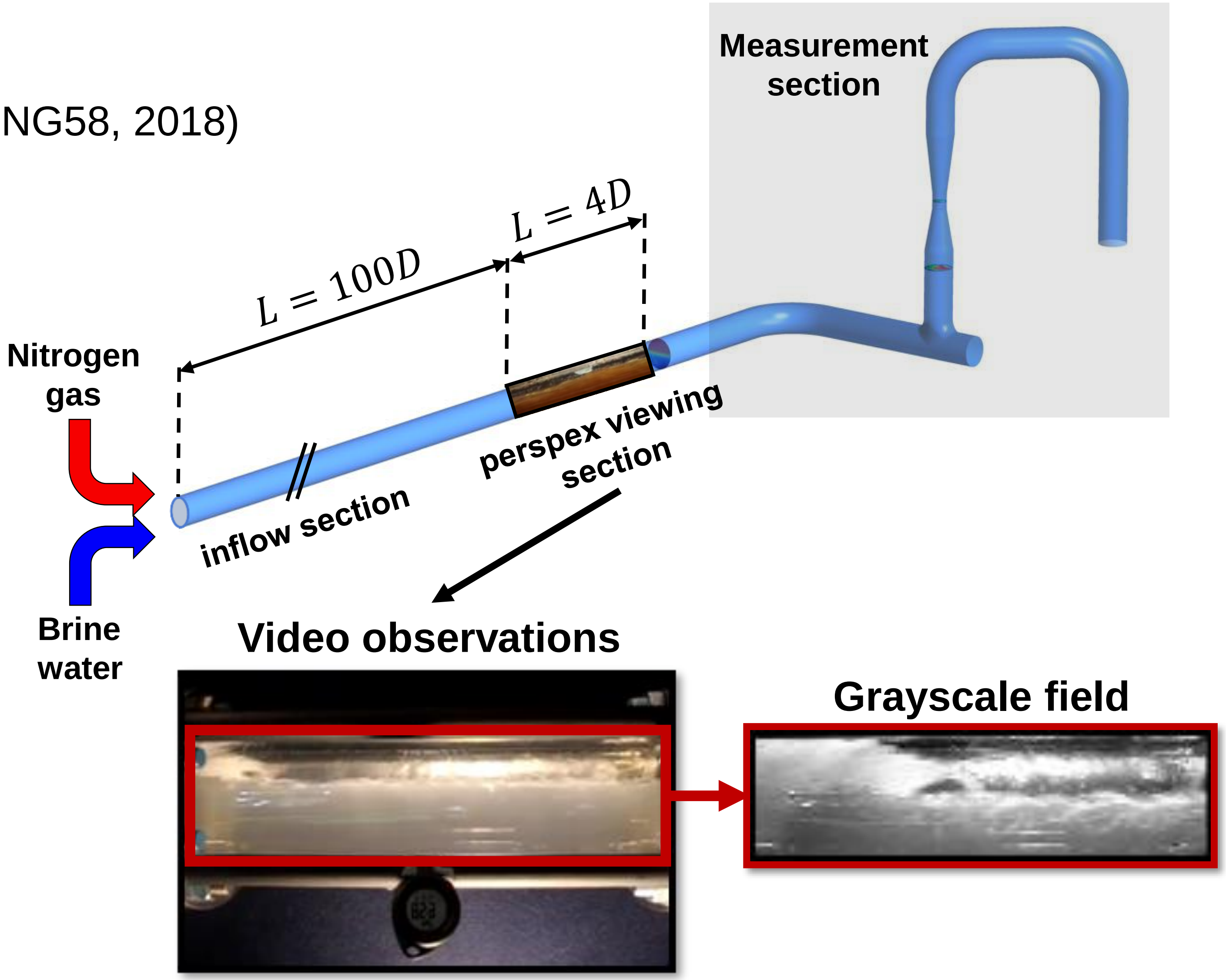
Set up:

- performed by TUV SUD NEL (JRP Report ENG58, 2018)
- nitrogen - brine water slug flow
- horizontal pipe $(L \approx 10m,\ D = 0.0972m)$
  followed by viewing section $(L \approx 4D)$
- avg. slug frequency $\frac{72\, slug}{50\, second} \approx\ 1.4\ \mathrm{Hz}$

- flow parameters and superficial velocities:

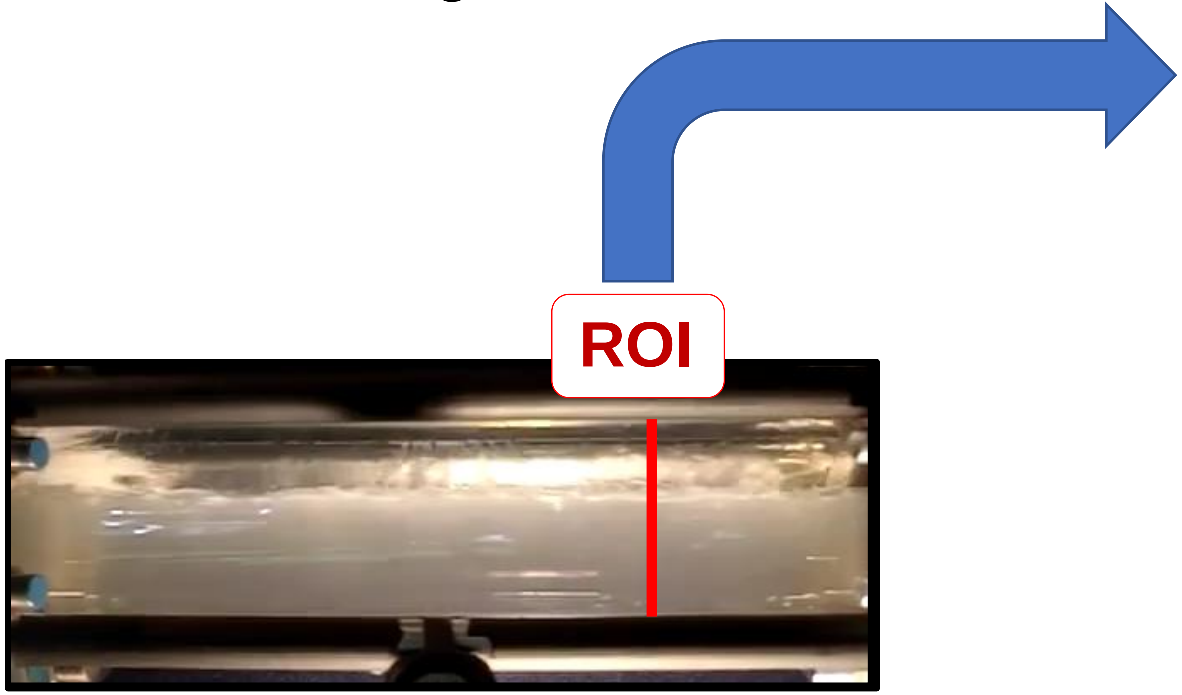
	Brine water	Nitrogen gas
density in $\frac{\mathrm{kg}}{\mathrm{m}^3}$	1011	10.8
dyn. viscosity in $\mathrm{Pa} \cdot \mathrm{s}$	$8.82 \cdot 10^{-4}$	$1.75 \cdot 10^{-5}$
superficial vel. in $\frac{\mathrm{m}}{\mathrm{s}}$	0.545	1.635

- data acquired for $50s$ at $240\ \mathrm{Hz}$



APPENDIX - Liquid level extraction

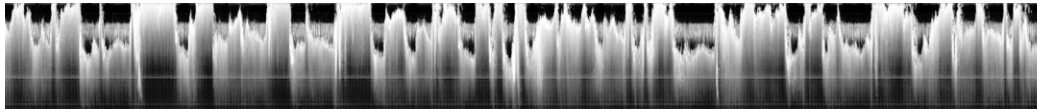
Brine water - nitrogen slug flow



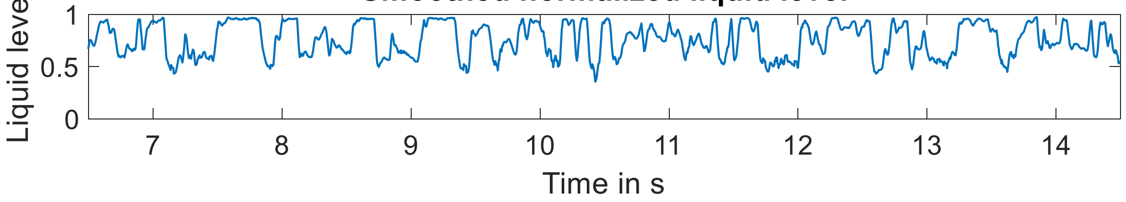
ROI over time

Gray scale of ROI over time

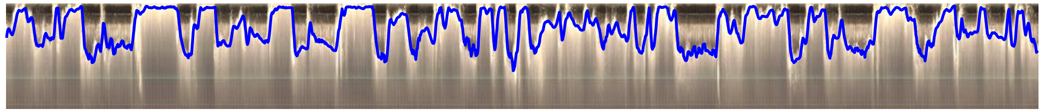
Result of Gaussian filter and contrast enhancement



Smoothed normalized liquid level



Comparison of liquid level and video



APPENDIX – Averaged translational velocity

- Collect pixel columns over time at inelt and outlet of the viewing section

INLET **OUTLET**

INLET

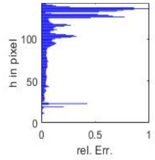
OUTLET

- Determine offset of inlet and outlet image by **cross-correlation**

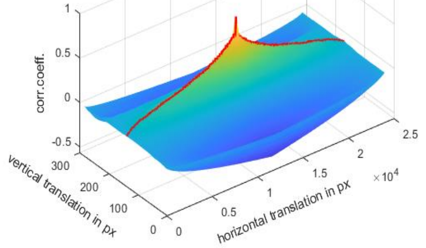
  ➡ offset ≅ #timesteps

- Derrive $\overline{v_s}$ with distance from inlet to outlet

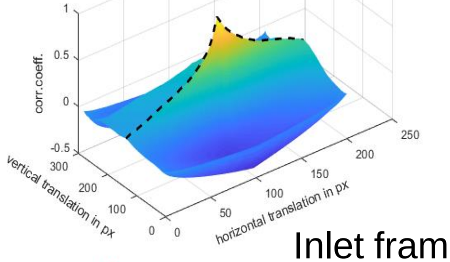
$\epsilon(h)$



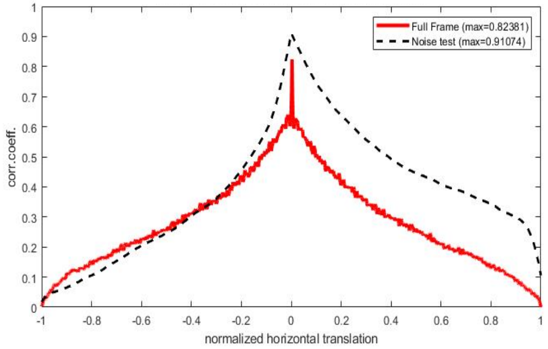
Cross-corr. Coeff $c(A,B)$



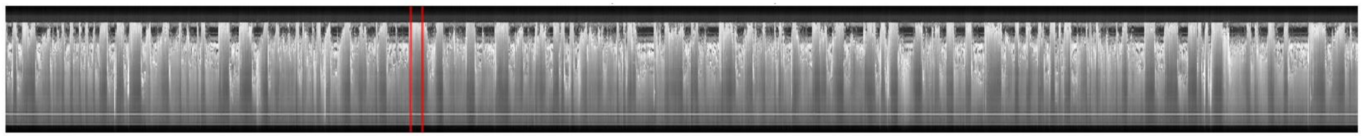
Cross-corr. Coeff (noise test)



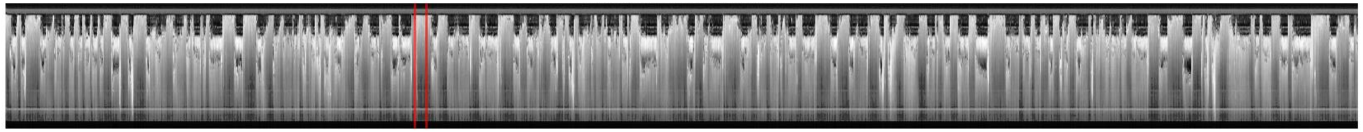
Cross-corr. Coeff $c(A,B)$ at maximal vertical value



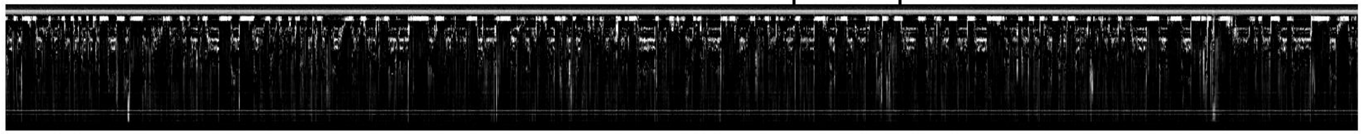
Inlet frame A



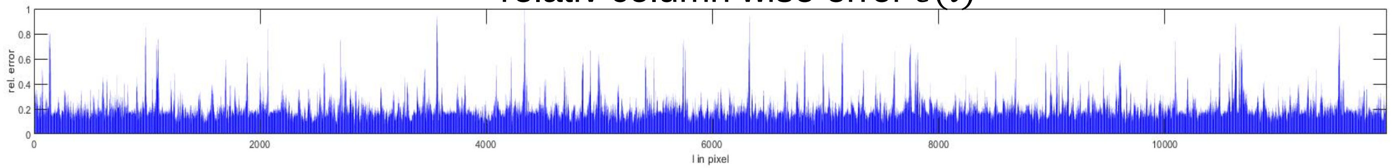
Outlet frame B



Pointwise error $|A-B|$

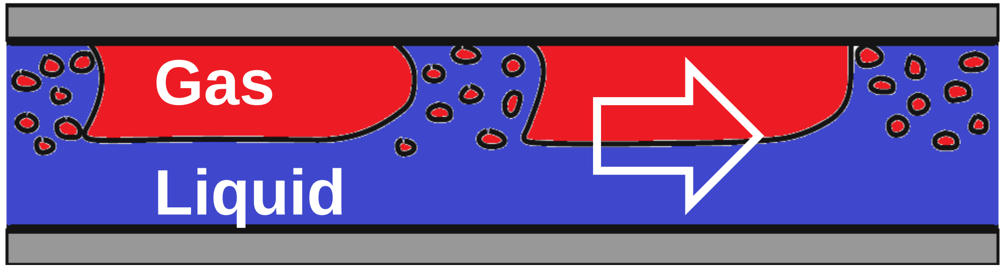


relativ column wise error $\epsilon(l)$

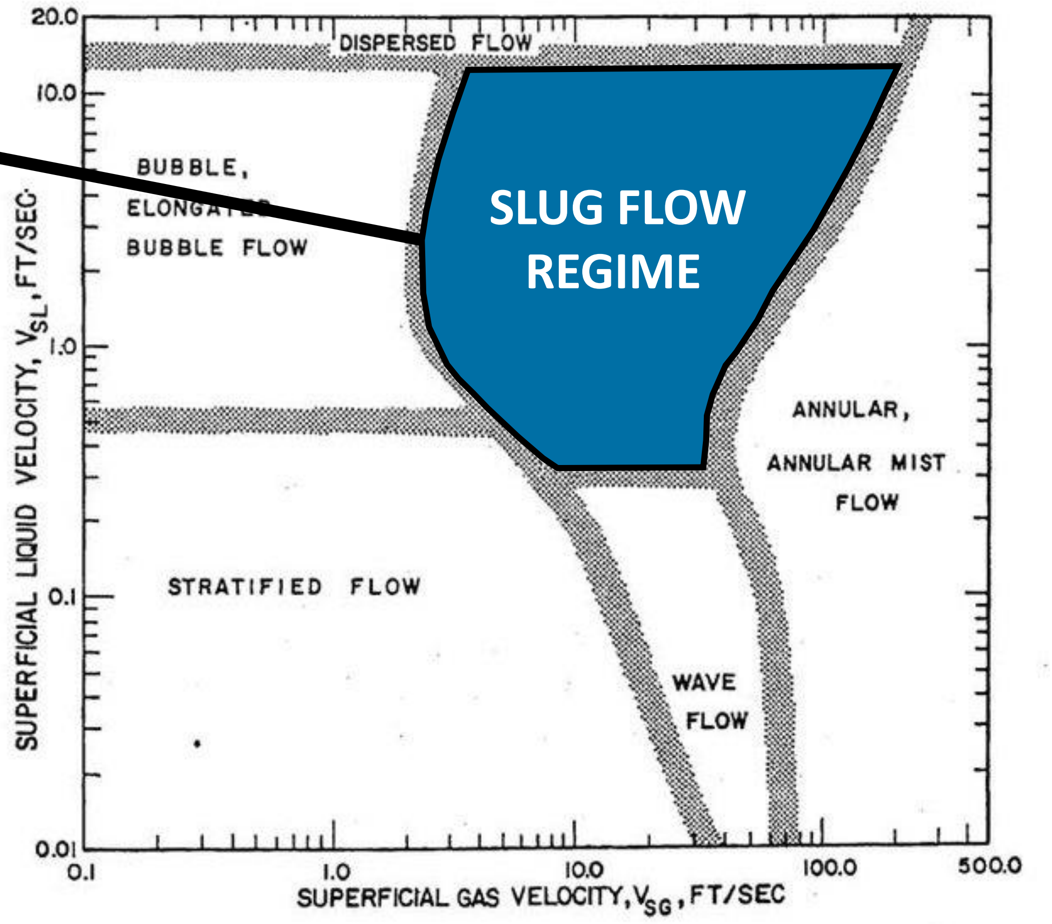


APPENDIX – Multiphase flow pattern

Slug flow regime



Flow pattern map **(Mandhane, 1974)**



Empiric flow pattern maps:

- pattern classified by superficial gas and liquid velocities
- non universal
- slug flow is 1 out of 6 flow pattern classes