Data Analysis of Hybrid Rocket Fuels Combustion Tests

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Experiments on new hybrid rocket fuels at DLR

- DLR investigates new hybrid rocket fuels on a paraffin basis.
- Combustion tests were performed with single-slab fuel with 20° forward facing ramp angle.
- **Aim:** better theoretical understanding and optimization of combustion process.

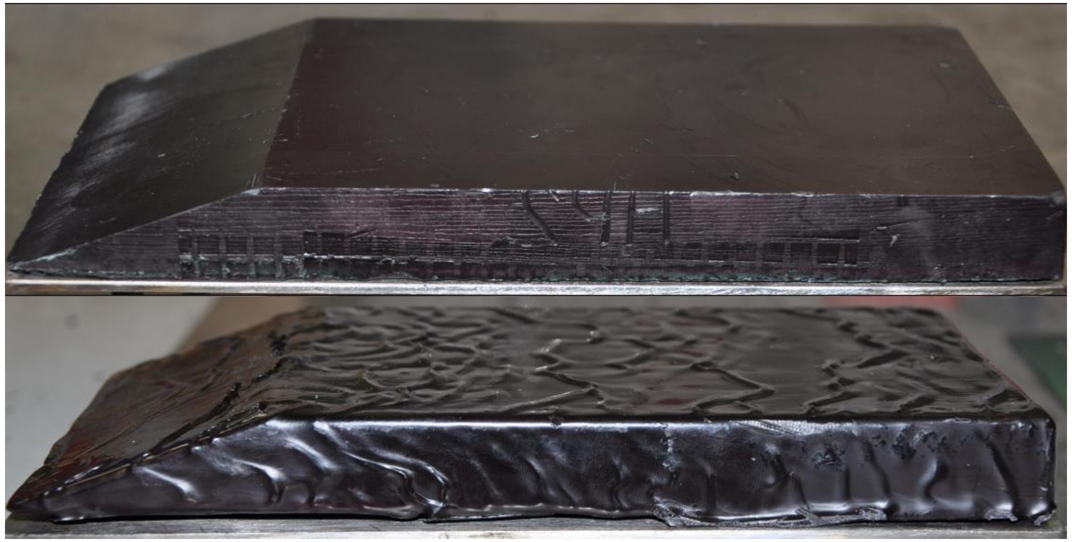


Fig. 1: Fuel slap configuration before (top) and after (bottom) combustion test.

Combustion chamber set-up

- Optically accessible combustion chamber is 450 mm long, 150 mm wide and 90 mm high.
- Tests were performed with different configurations (e.g. fuel, oxidizer mass flow, filters)
- Combustion is captured with high-speed video camera with 10 000 frames / second

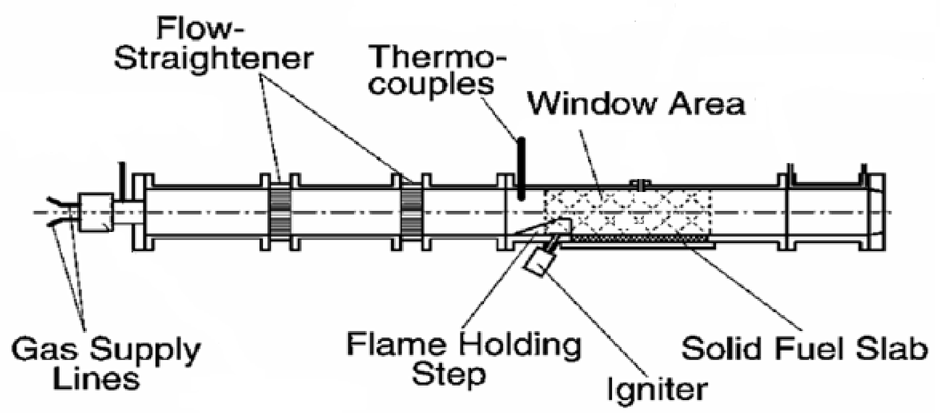


Fig. 2: Side view of combustion chamber

Test no.	Fuel		$\dot{m}_{Ox}[g/s]$		CH* filter
	6805	6805+5% polymer	10	50	
284	✓			✓	✓
289		✓		✓	✓
296		✓	✓		✓
243		✓	✓		

Fig. 3: Test matrix used for data analysis

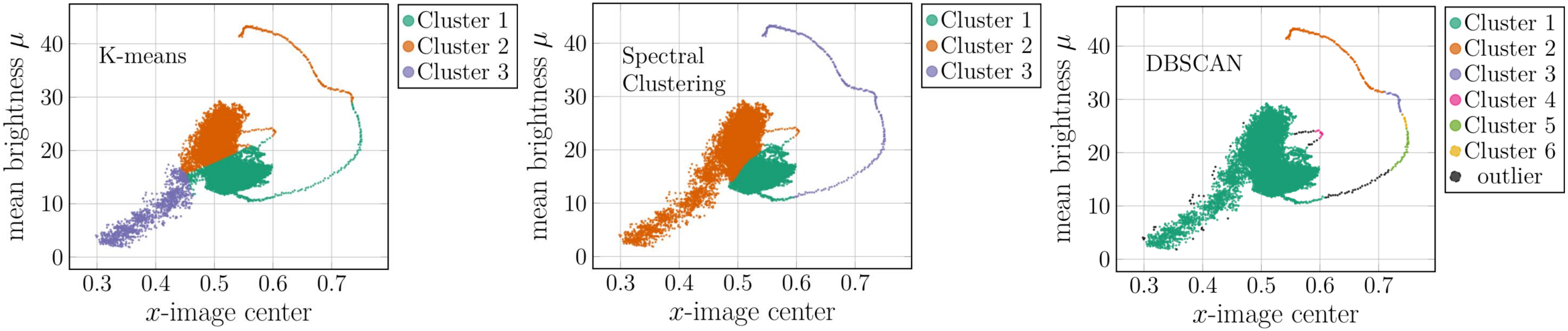
Test 284

Video:
(test extract)

fuel = pure paraffin 6805
oxidizer mass flow = 50 *g/s*,
CH*-filter (i.e. wavelengths emitted from CH* are filmed)
test 3s = 30 000 frames / 8GB data per test

Clustering of combustion image data

- Clustering of combustion data = identify different phases of the flow.
- Various clustering algorithms exist in the literature (DBSCAN, spectral clustering, k-means, …).
- **Start:** Comparison of algorithms on two features $(\mu, \overline{x})_j$ for all $j = 1, \dots, 30000$ images of test 284.



computing time ≈ $0.8\ s$

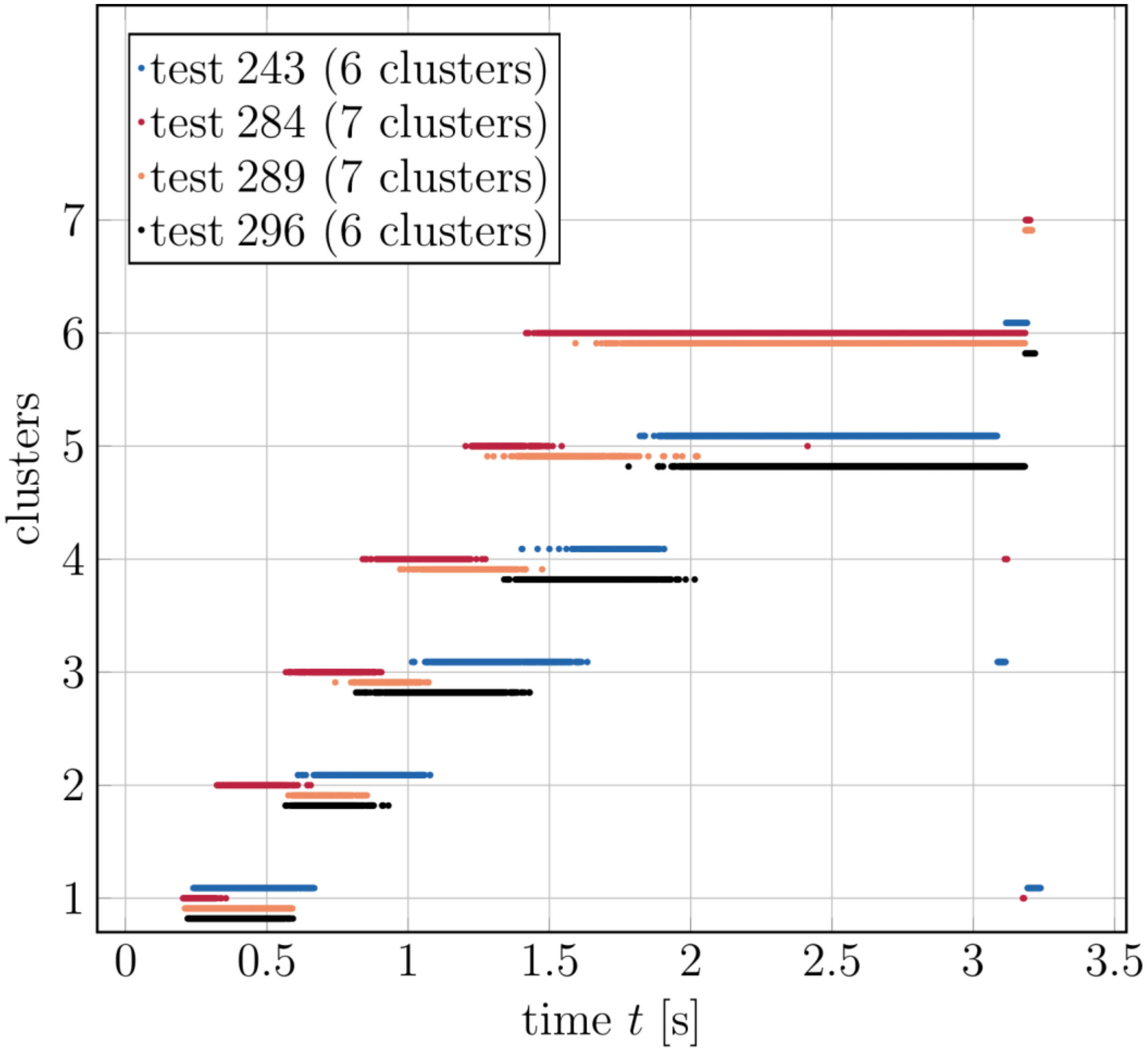
computing time ≈ $70\ s$

Strategies to avoid drawbacks of K-means

- **Avoid local optimum solutions**
  - Algorithm is run multiple times (here: 10-times)
  - Take solution with smallest objective function (not a big difference in our case)
  - Implementation of K-Means++*
    - Choose the initial centers less randomly

- **Selection of K in K-means?**
  - Detailed analysis of objective function depending on K (here: algorithm is used for K= 2, …, 10)
  - Runtime of algorithm scales at least linearly in K
  - Note that an optimal K is often problem dependent

*Arthur and Vassilvitskii. K-means++: The advantages of careful seeding. SODA ’07, 2007

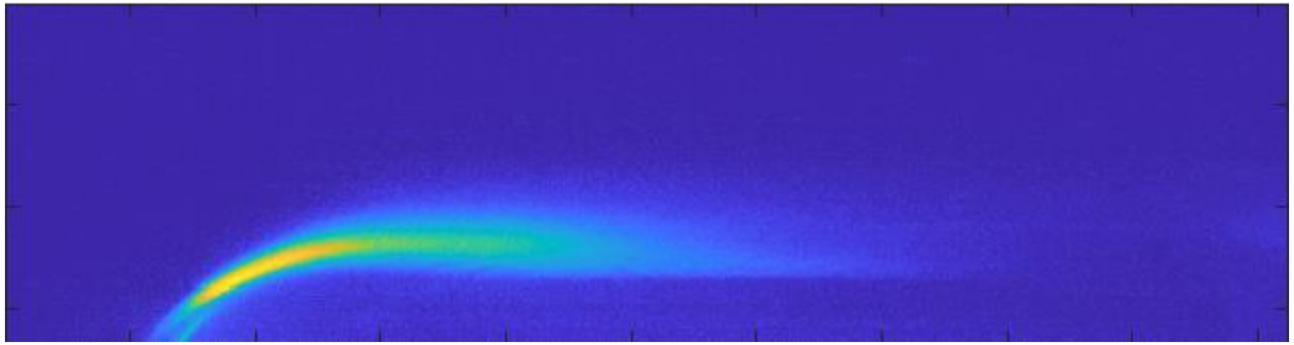


Test	C_1	C_2	C_3	C_4	C_5	C_6	C_7
243	0.47	0.4	0.55	0.3	**1.21**	0.08	x
284	0.13	0.26	0.29	0.35	0.25	**1.7**	0.02
289	0.38	0.23	0.21	0.36	0.39	**1.4**	0.03
296	0.36	0.29	0.51	0.55	**1.25**	0.04	x

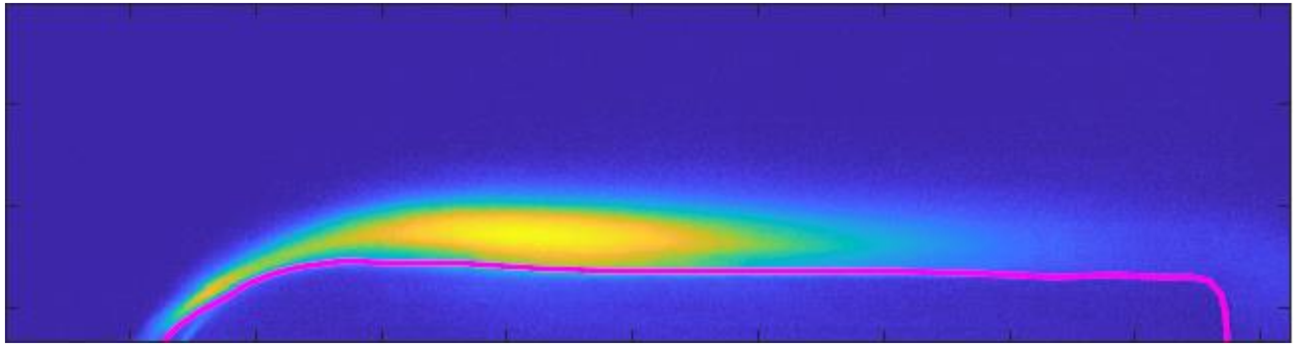
Fig. 4: Distribution of frames to their corresponding clusters.

Fig. 5: Time length of each cluster [s].

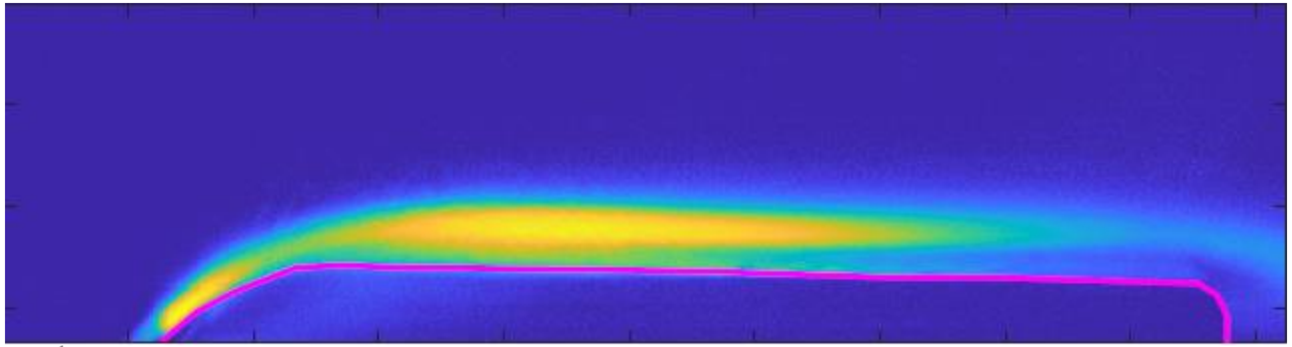
Test 284 with K=7 (Part 1/3)



cluster 1
(1320 / 30000 frames)
ignition phase
(ignition comes from bottom of the chamber)

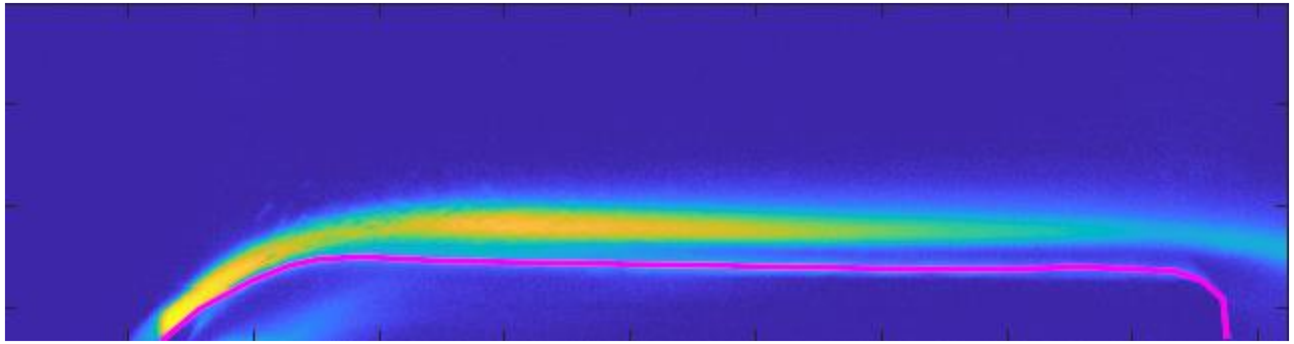


cluster 2
(2942 / 30000 frames)
burn phase without energy from outside
(ignition valves closed)

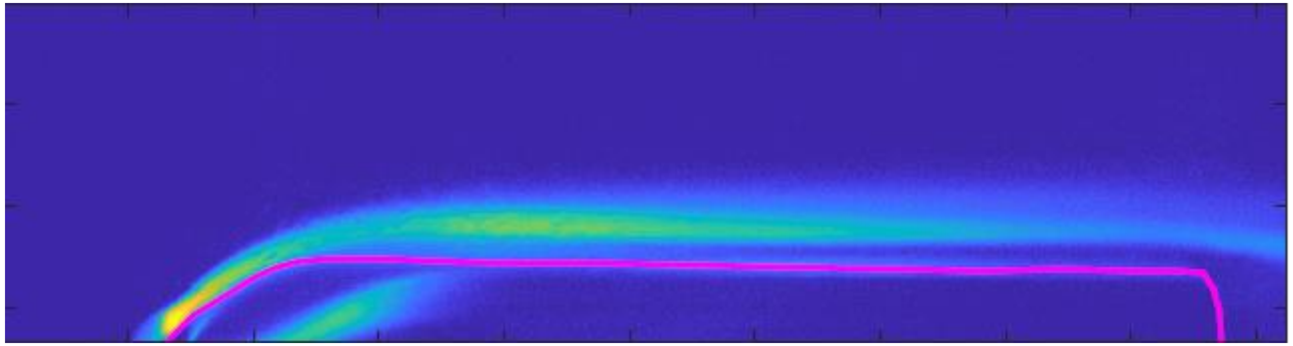


cluster 3
(3493 / 30000 frames)
fuel slap burns in the middle
(oxygen mass flow increases)

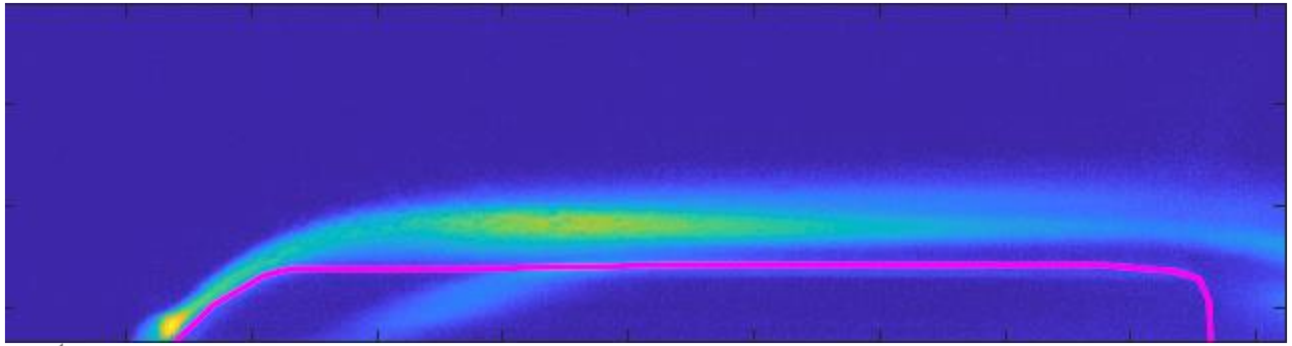
Test 284 with K=7 (Part 2/3)



cluster 4
(3493 / 30000 frames)
whole surface is burning (brightness decreases due to $CH^* + O_2 = CO + OH^*$)

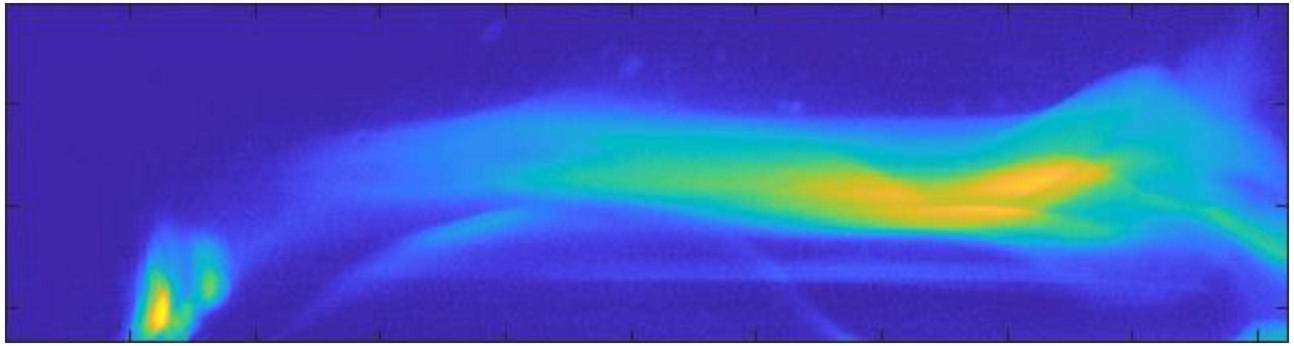


cluster 5
(2452 / 30000 frames)
large side flame close to camera



cluster 6
(16980 / 30000 frames)
constant combustion (with low CH* concentration, largest cluster in time)

Test 284 with K=7 (Part 3/3)



cluster 7
(194 / 30000 frames)
flame extinguishing phase (oxygen valve closes, nitrogen purge)

Conclusion and outlook

- Analysis of turbulent combustion tests in combustion chamber allows a quantitative comparison.
- Clustering with K-means++ on workstation required $\approx$ 1.5 days per test.
- **Recently:** Further clustering results with spectral clustering on HPC-cluster at DLR (more short-time phenomena revealed).
- **Further details:** Rüttgers, Petrarolo and Kobald (2020) *Clustering of Paraffin-Based Hybrid Rocket Fuels Combustion Data*. Experiments in Fluids, 61:4

Thank you for your attention!