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

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Fuel</th>
<th>$\dot{m}_{O_x}$[g/s]</th>
<th>CH* filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6805</td>
<td>6805+5% polymer</td>
<td>10</td>
</tr>
<tr>
<td>284</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>289</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>296</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>243</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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 \((\mu, \bar{x})_j\) for all \(j = 1, ..., 30000\) images of test 284.

computing time \(\approx 0.8\ s\)  
computing time \(\approx 70\ s\)
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 $K= 2, \ldots, 10$)
  • Runtime of algorithm scales at least linearly in $K$
  • Note that an optimal $K$ is often problem dependent

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^*+O2 = 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 ≈ 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!