143:Process Failure Detection via Recurrence Quantification Analysis

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Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

Outline

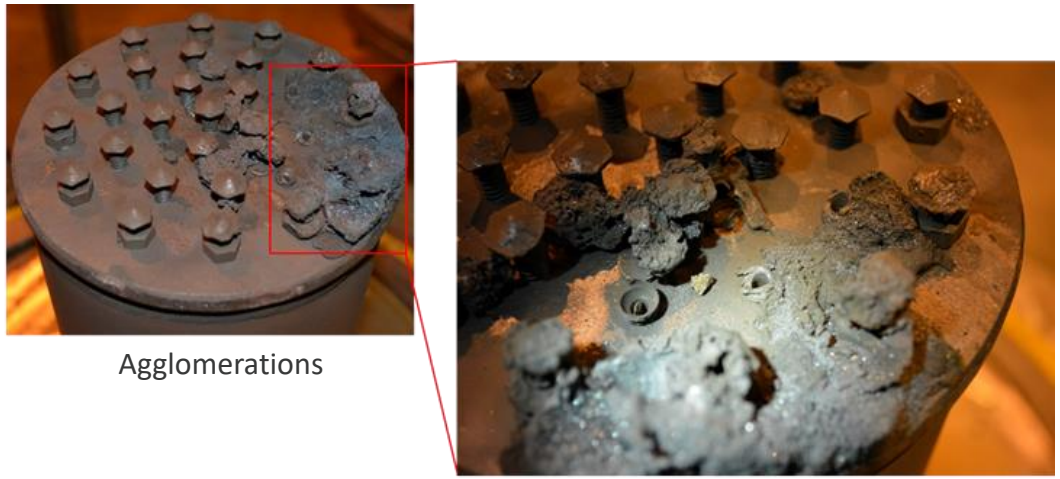
- **Introduction: Process failures in gas-solid flow systems**
- **Recurrence Plots and RQA: What are they?**
- **Inspiration for current study**
- **Experiments**
  - Small Slot-Rectangular Spouted Bed
  - Bubbling Fluidized Bed
- **Conclusions**

Introduction: Process failures in gas-solid flow systems

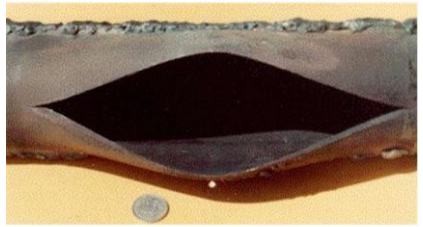
Process Failure

- General term for anything that creates a process/ quality/safety abnormality that necessitates a plant shutdown and/or production slow-down
- Many possible causes
  - Fatigued/failed components
  - Off-nominal operating conditions (pressure, temperature, etc)

The objective of this study was to test the feasibility of using Recurrence Plots (RP) and Recurrence Quantification Analysis (RQA) as a means of detecting some process failure conditions.



Agglomerations



Tube Failures

Refractory Failures

Recurrence Plots

- Compares each point in the data series to every other point.

$$R(i,j) = \begin{cases} 1, & if \quad \|\vec{x}(i) - \vec{x}(j)\| \leq \varepsilon \\ 0, & otherwise \end{cases}$$

Very sensitive

- Diagonal lines denote periodicity
- Vertical/horizontal lines indicate that the state of the system is unchanging, or changing slowly.
- Uncorrelated noise represented by patterns of single black dots.
- Process can be deterministic if diagonal lines exist beside single isolated points.
- Process can be chaotic if diagonal lines are periodic (represents unstable periodic orbits).
- Used in a variety of science and medical fields:
  - Cardiac and neuroscience
  - Financial exchange rates
  - Damage detection
  - Fluidized bed regime identification

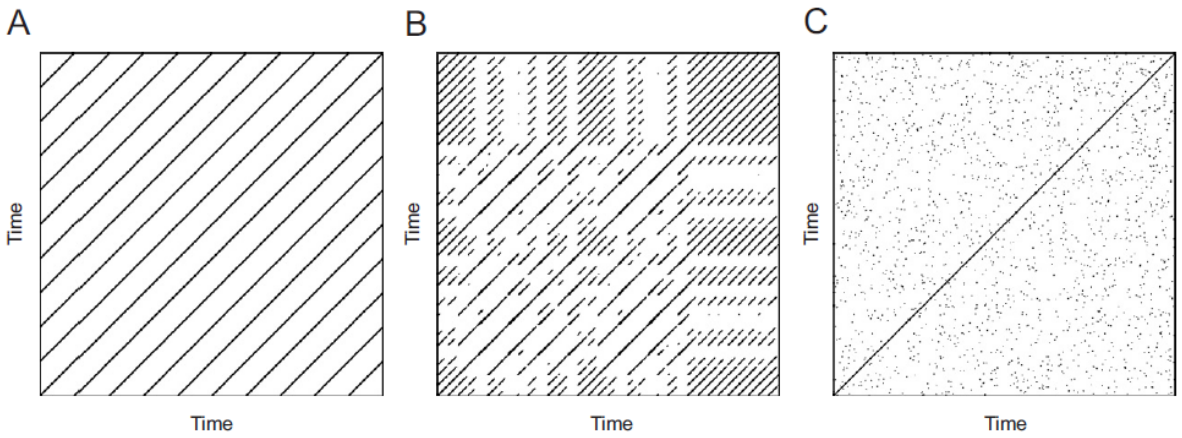


Fig. 1. Recurrence plots of (A) a periodic motion with one frequency, (B) the chaotic Rössler system (Eq. (A.5) with parameters $a = b = 0.2$ and $c = 5.7$) and (C) of uniformly distributed noise.

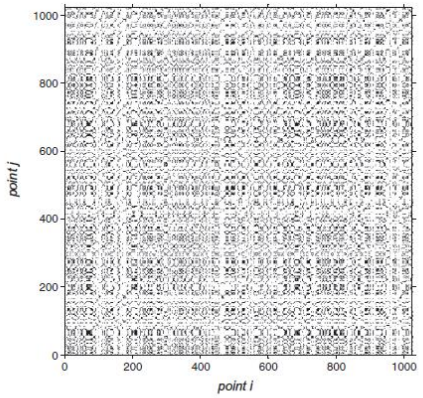


Fig. 5. Recurrence plot for bubbling regime when $u/u_{mf} = 2.18$, $P = 101.3$ kPa and particle diameter of 225 μm, $L/D = 1.71$, $N = 10{,}000$ and $\varepsilon = 0.1$.

Marwan, N.; Romano, M.C.; Thiel, M.;Kurths, J. (2007) Recurrence plots for the analysis of complex systems, Physics Reports, Vol. 438, pp. 237-329.

Recurrence Quantification Analysis (RQA)

- **Recurrence Rate (RR)**
  - Percentage of recurrence points that fall within the specified tolerance.

$$RR = \frac{1}{N^2}\sum_{i,j=1}^{N} R(i,j)$$

- **Determinism (DET)**
  - Percentage of recurrence points that form diagonal lines (low for stochastic systems, high for periodic systems)

$$DET = \frac{\sum_{\ell=\ell_{min}}^{N} \ell P(\ell)}{\sum_{\ell=1}^{N} \ell P(\ell)}$$

- **Divergence (DIV)**
  - Inverse of the maximum diagonal line length.

$$DIV = \frac{1}{L_{max}}$$

- **Laminarity (LAM)**
  - Percentage of recurrence points that form vertical lines of specified length. (vertical lines denote a state that is either unchanging, or changing slowly)

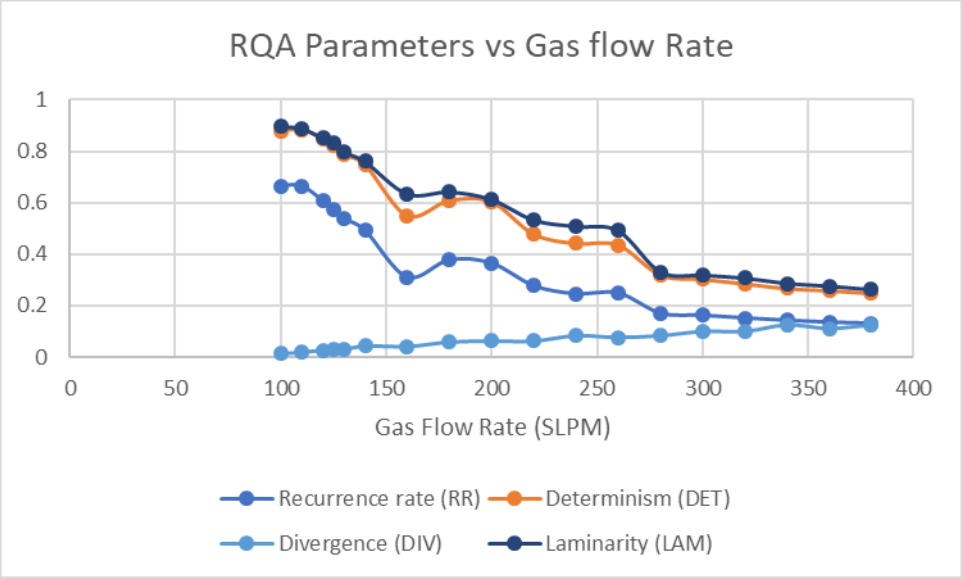
$$\text{LAM} = \frac{\sum_{v=v_{min}}^{N} vP(v)}{\sum_{v=1}^{N} vP(v)}$$

- **Trapping Time (TT)**
  - Average length of vertical lines which are equal to or greater in length to a specified minimum length. Represents the average time the system is "trapped" in a specific state.

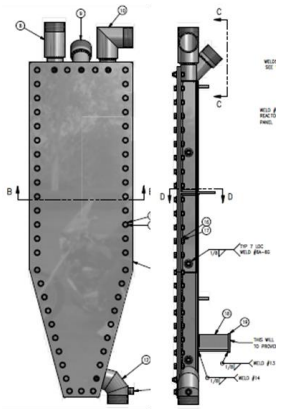
$$TT = \frac{\sum_{v=v_{min}}^{N} vP(v)}{\sum_{v=v_{min}}^{N} P(v)}$$

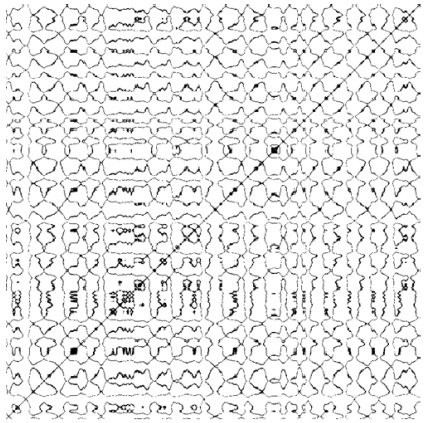
- **Entropy (Entropy)**
  - Measurement of the complexity of the system. (uncorrelated noise will have low entropy values)

$$ENTR = -\sum_{l=l_{min}}^{N} p(l) ln p(l)$$



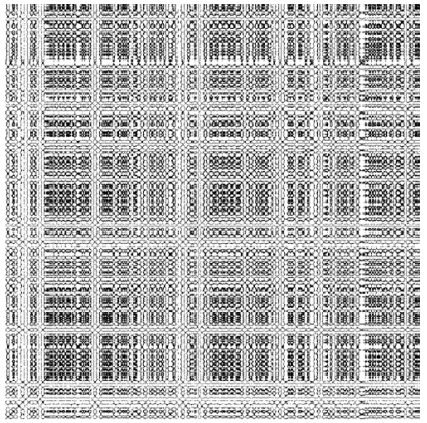
Inspiration: Spouted Bed Reactor Failure





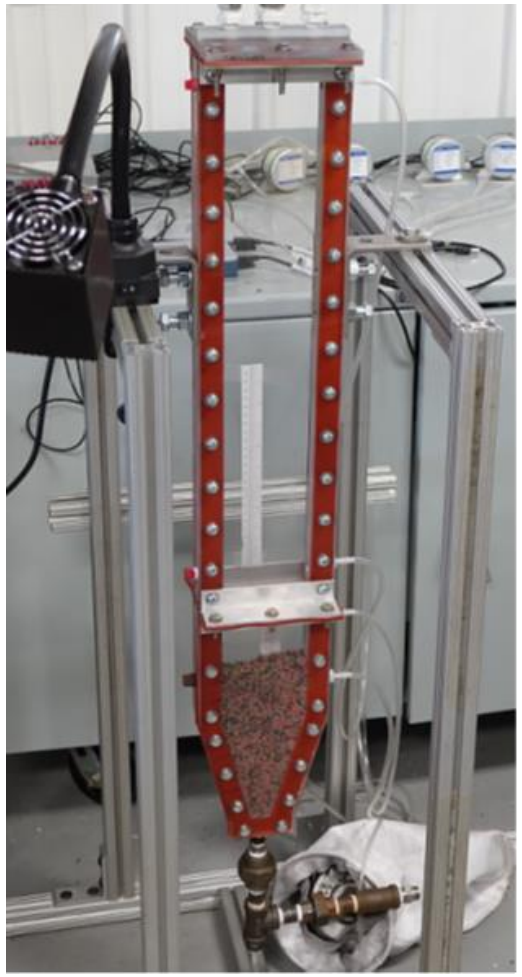
RR	0.086
DET	.599
DIV	0.063
DET/RR	6.966
LAM/DET	1.252

Blown Rupture Disc



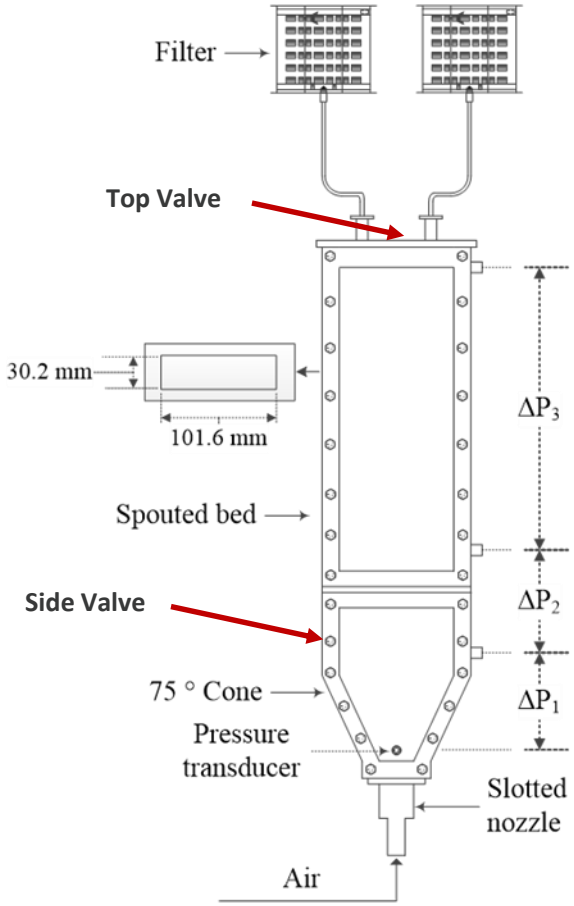
RR	0.298
DET	0.734
DIV	0.043
DET/RR	2.457
LAM/DET	1.163

Small Spouted Bed: Experimental Setup



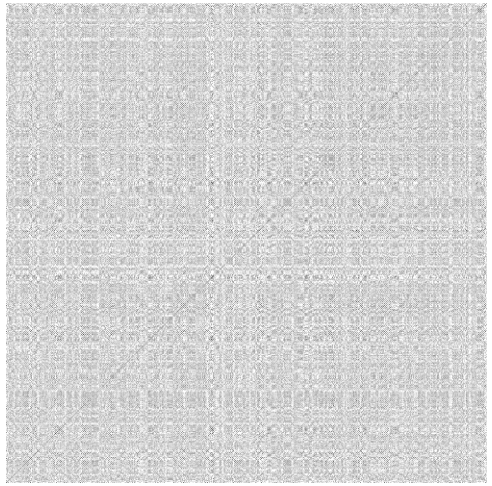
Rectangular spouted bed with a interchangeable cone section

- Bed cross-section - 4” x 1 3/16”
- Upper section height – 24”
- Cone angles (from horizontal)
  - 45°, 60°, 75°
- **3-D Printed Nozzles of various sizes.**
- **Swage-lok valves added to side and top to simulate air leaks.**
- **Hepa filtration of exhaust gas.**

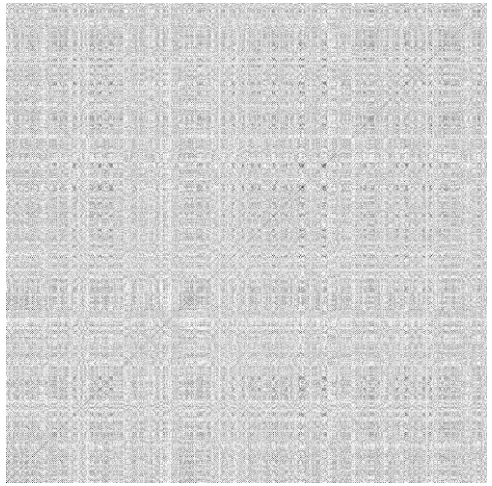


Small Spouted Bed Results:

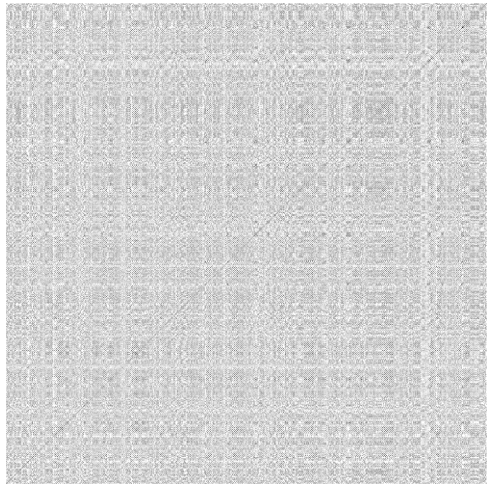
Nominal



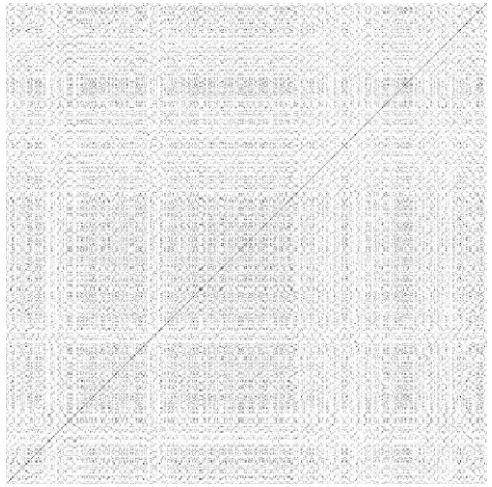
Side Valve Open

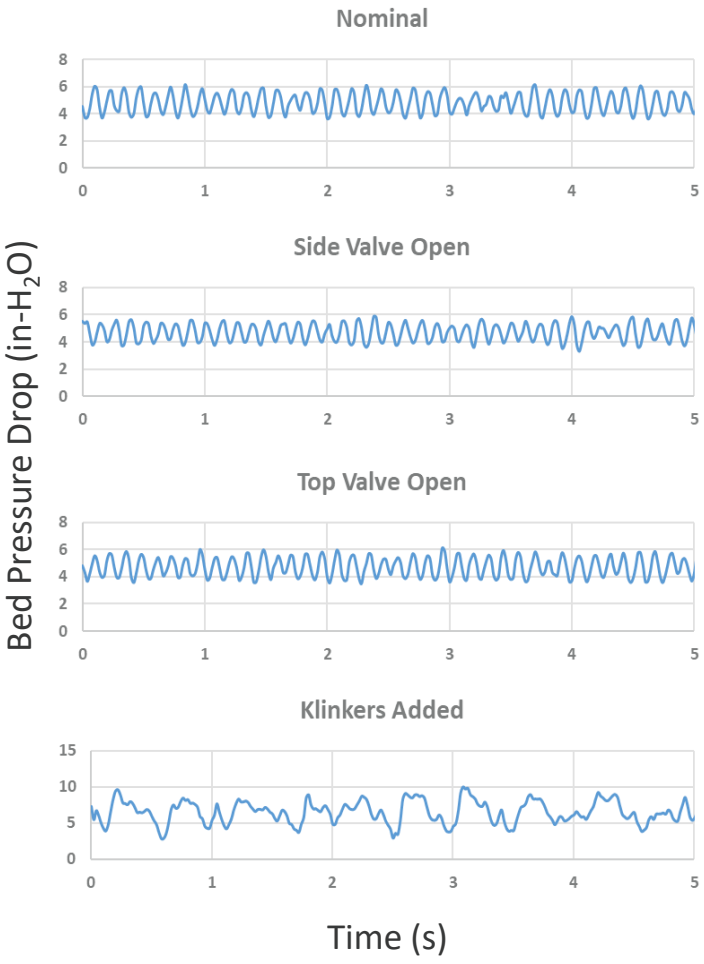


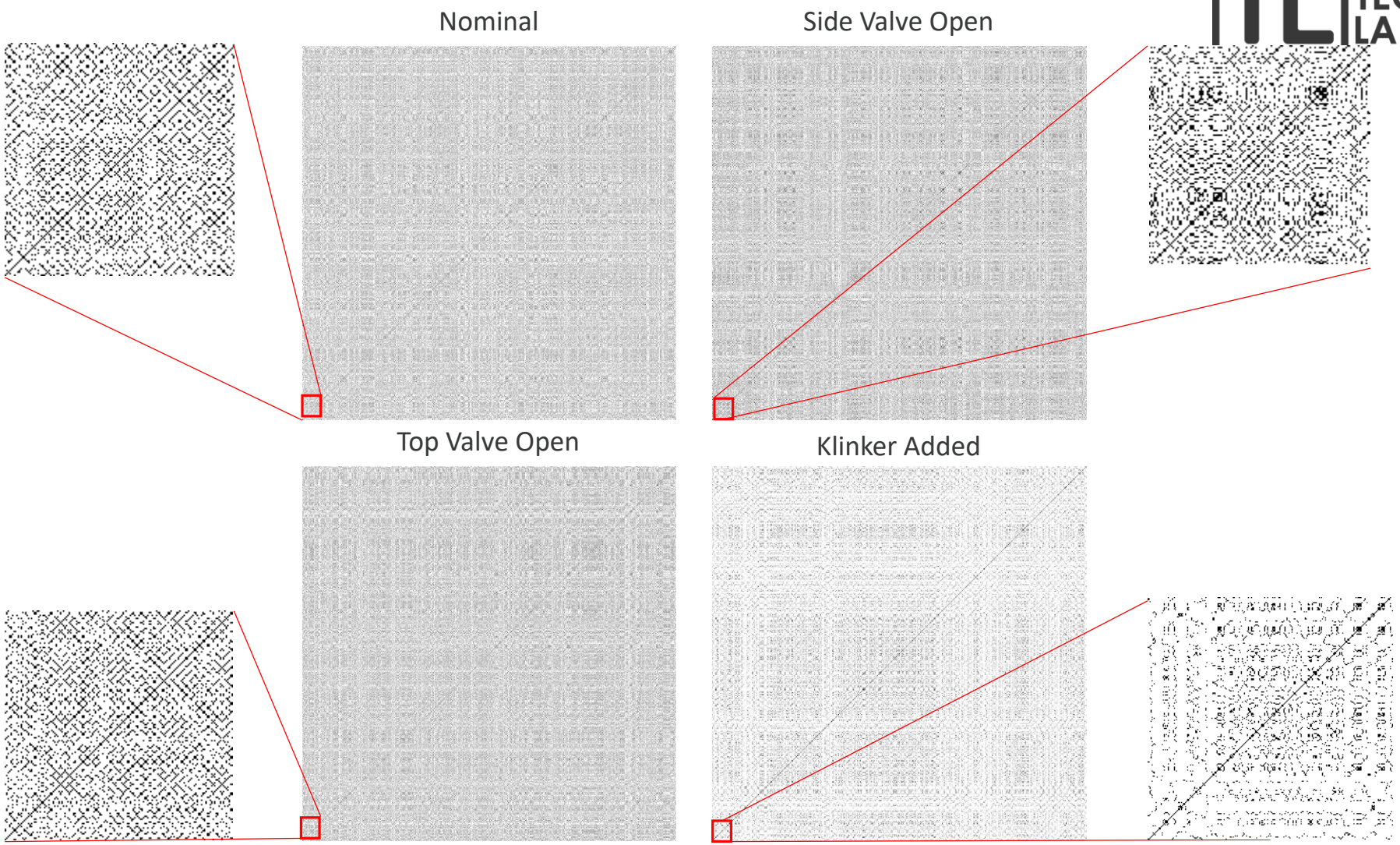
Top Valve Open



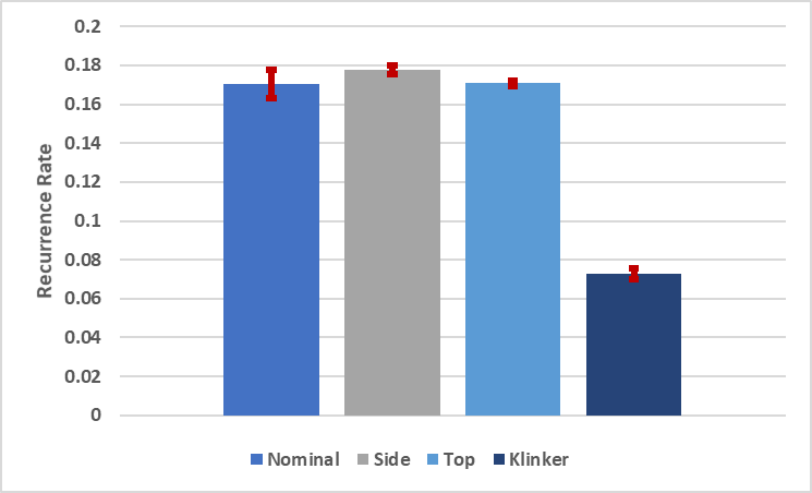
Klinker Added

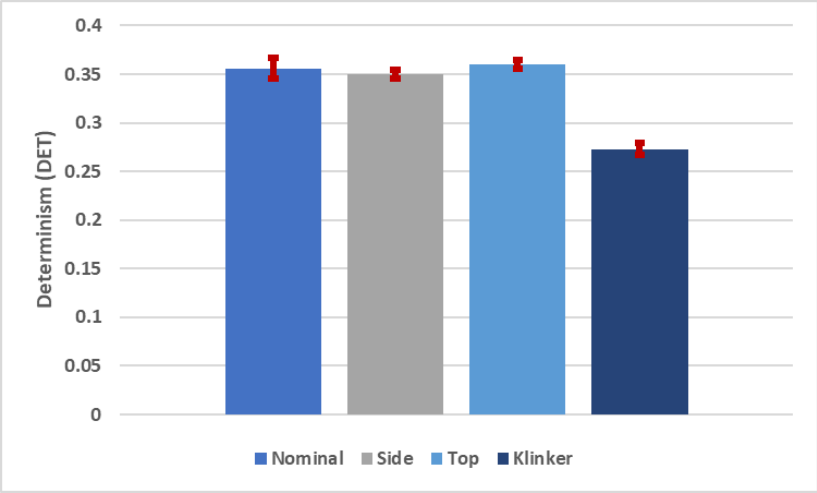


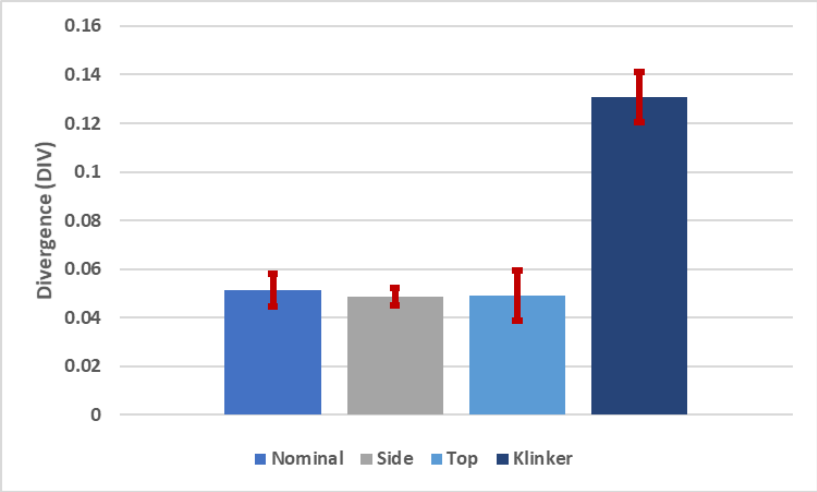


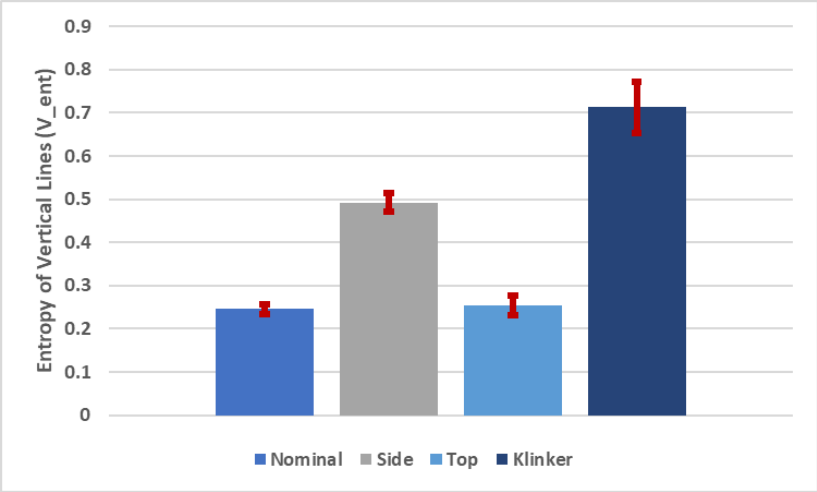

Nominal
Side Valve Open
Top Valve Open
Klinker Added

Small Spouted Bed Results:

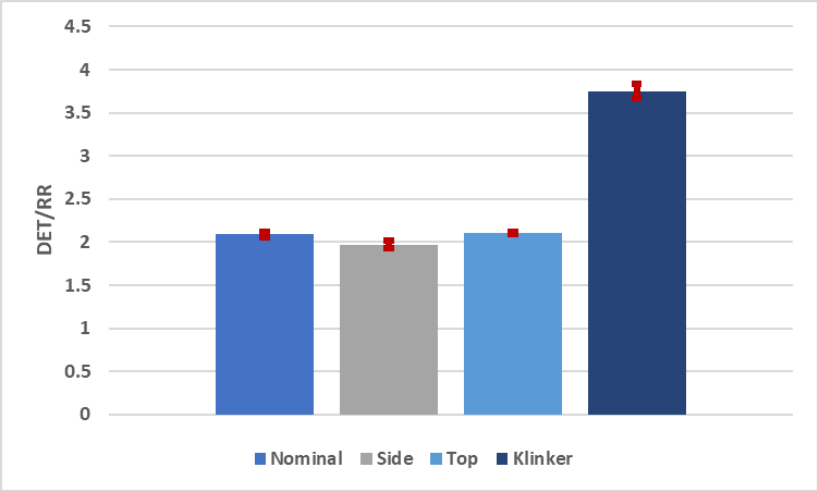


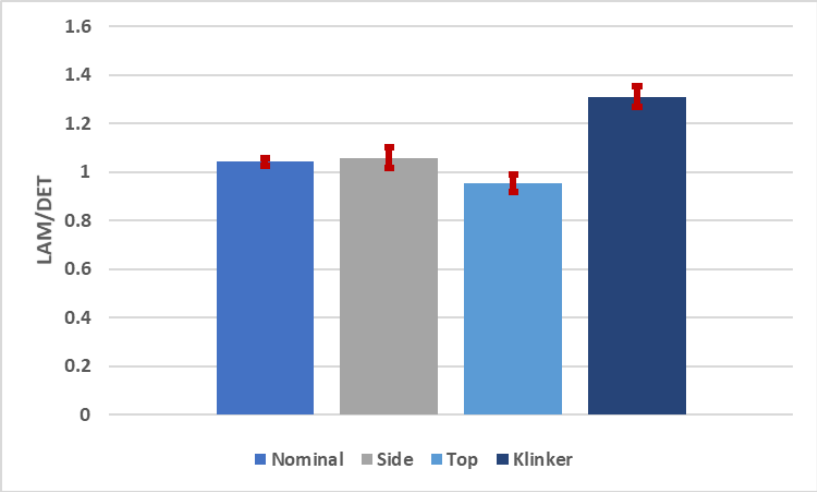






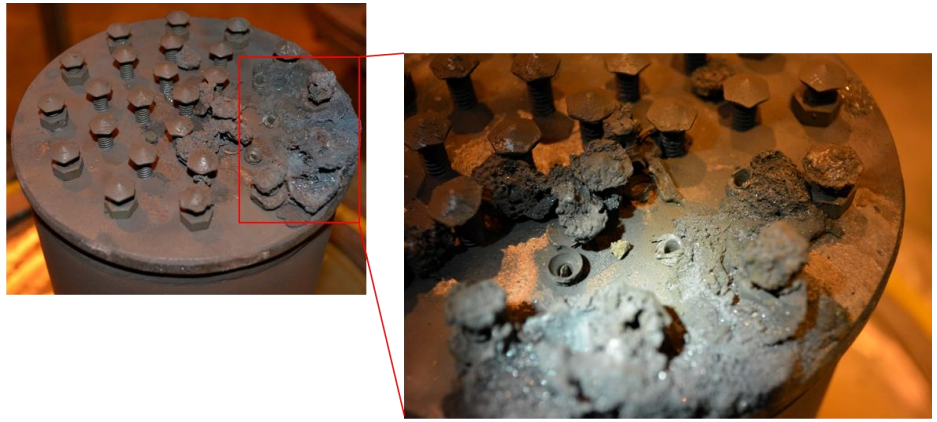
Small Spouted Bed Results:



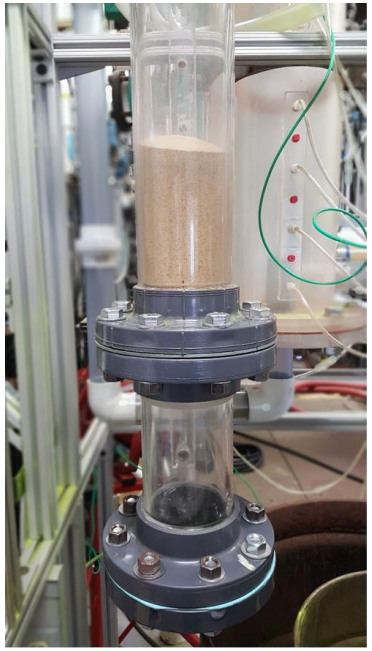


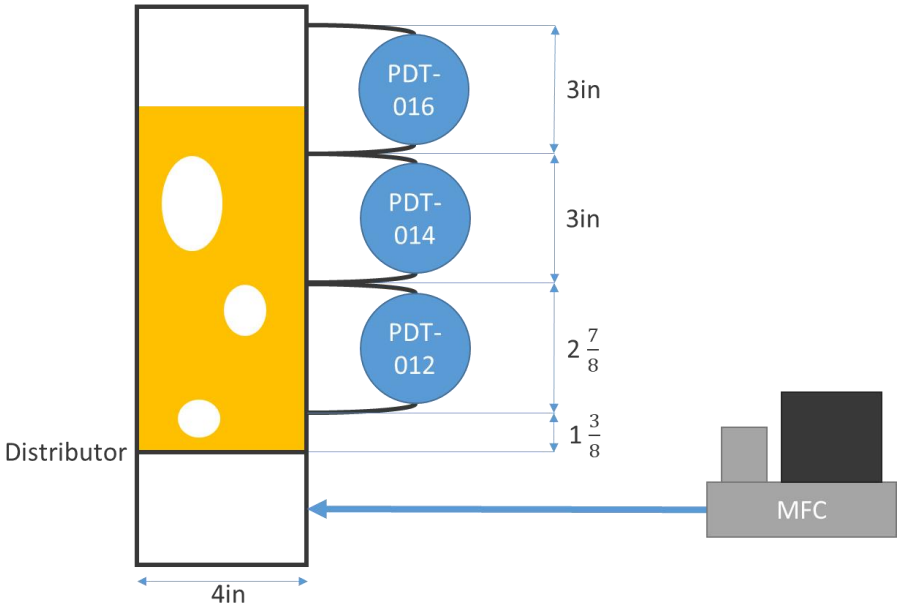
- The klinker case is easily distinguishable from the nominal and side/top leakage cases.
- The non-klinker cases are harder to distinquish.
- The side valve/leak case is readily visible when considering the entropy of vertical lines metric.
- The top valve/leak case is mostly indistinguishable from the nominal condition, except for in the LAM/DET figure.

Sensitivity to Klinker Addition: Bubbling Bed



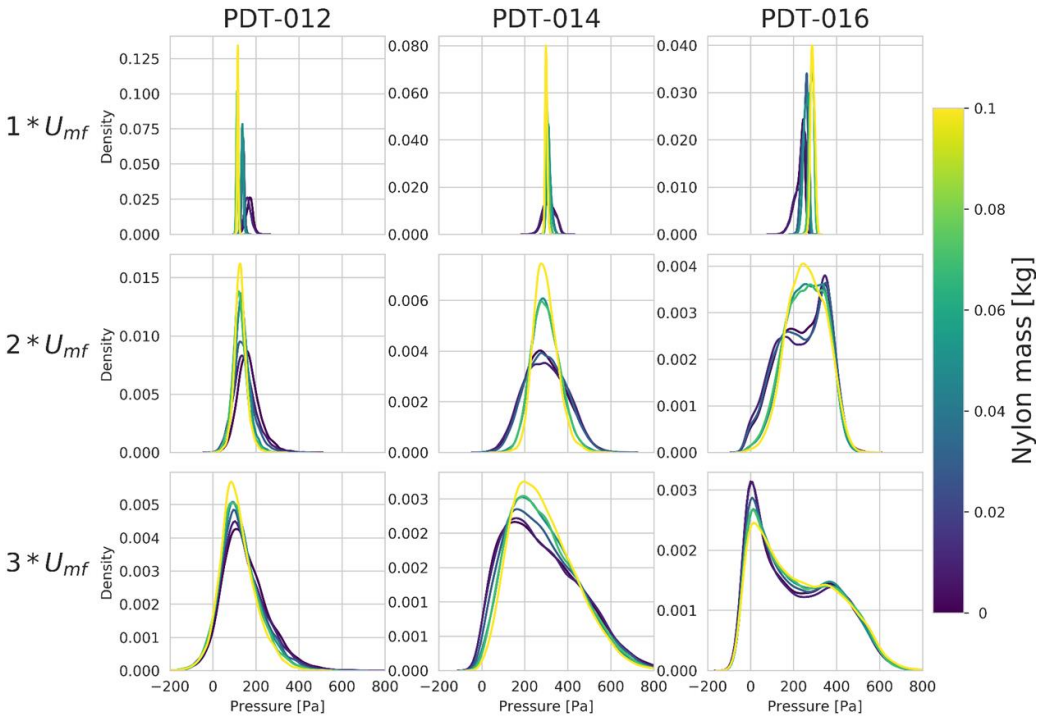
Agglomerations in NETL's Chemical Looping Reactor



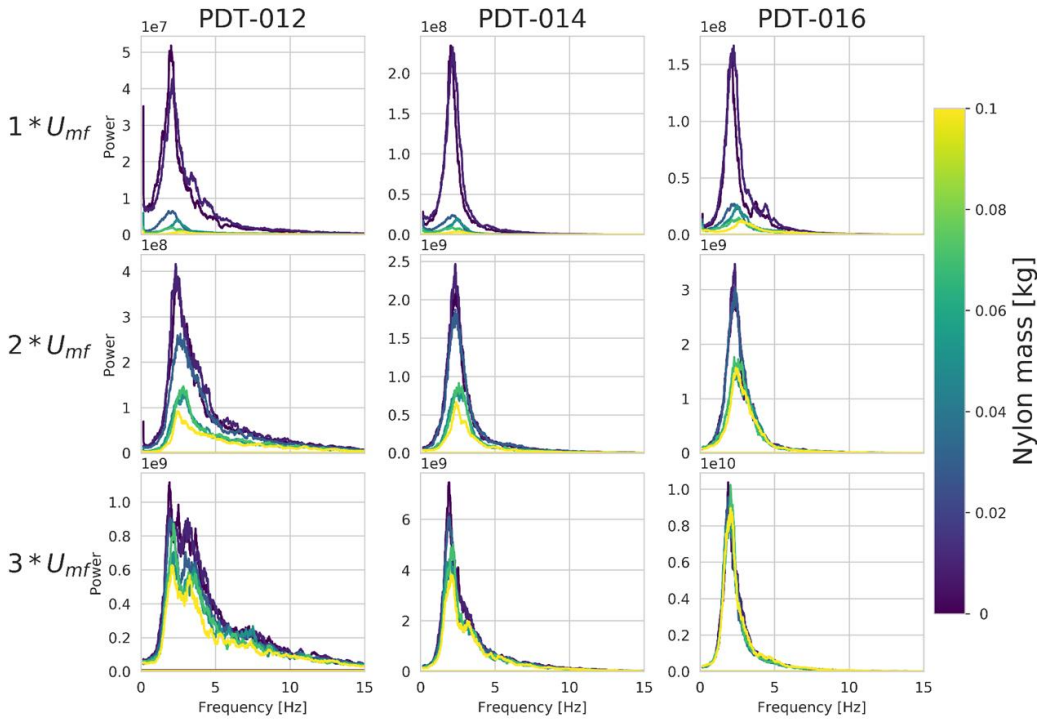


	Umf [cm/s]	SMD [µm]	p [g/cm³]	
HDPE	17.35	878	0.83	Bed material
Nylon	94.33	3275.96	1.13	Agglomerates

Bubbling Bed Test Results

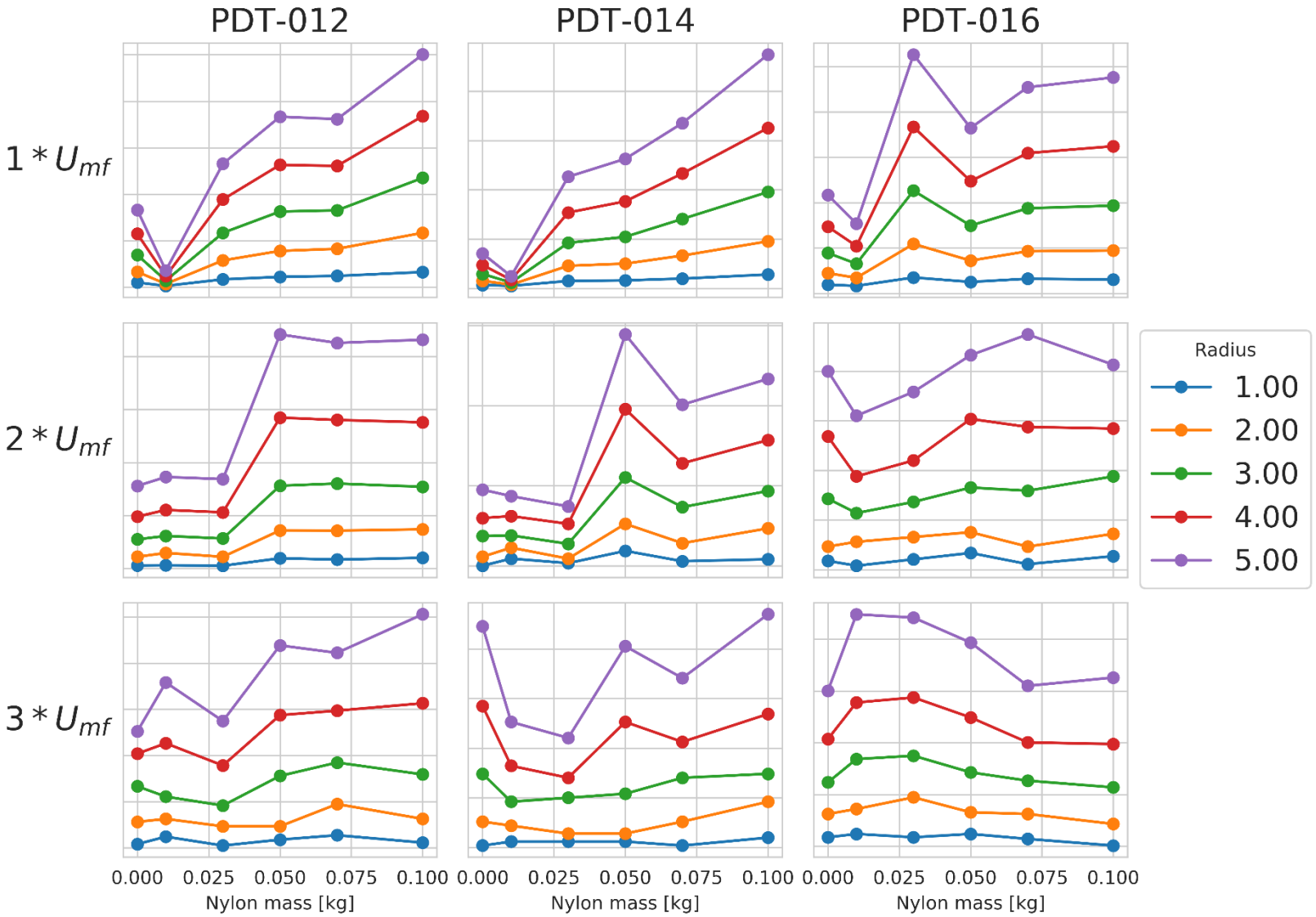


As nylon mass increases, distributions get wider



Spectral energy decreasing with increasing nylon mass

Bubbling Bed Test Results



$$RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R(i,j)$$

$$R(i,j) = \begin{cases} 1, & if \quad \|\vec{x}(i) - \vec{x}(j)\| \leq \varepsilon \\ 0, & otherwise \end{cases}$$

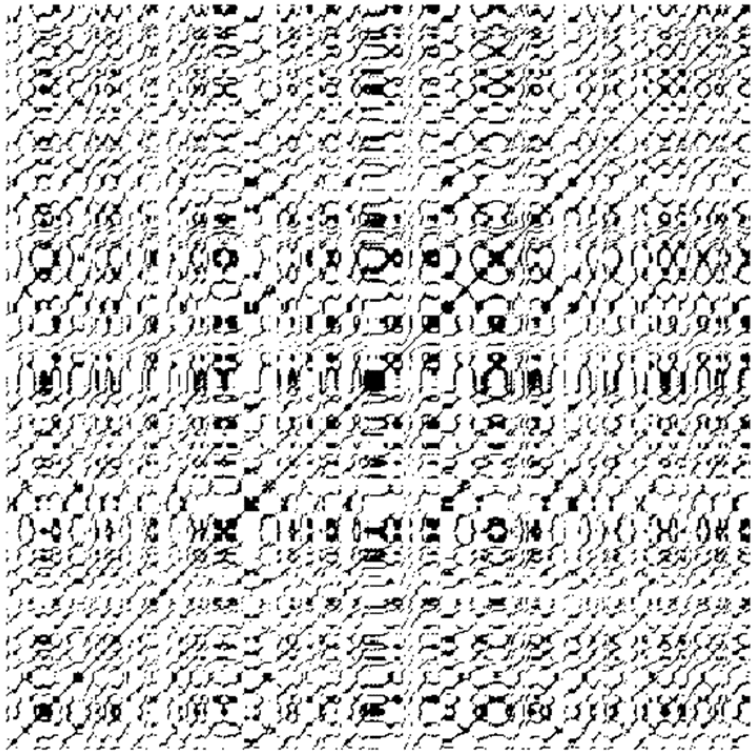
Generally, the recurrence rate increases with increasing nylon mass

However, very sensitive to radius.

Conclusions

Preliminary process failure data was obtained from both spouted and bubbling fluidized beds and compared to non-failure, or nominal, states.

- Recurrence Plots and Recurrence Quantification Analysis are shown to be sensitive to changes in system dynamics.
- Addition of large klinkers/agglomerations of solids is easily seen in nearly all RQA parameters.
- Gas leakage is harder to detect when the leak does not significantly change the system dynamics.
- Physical failures (such as blown rupture discs), can lead to large changes in system dynamics, and RQA results.



ACKNOWLEDGEMENTS

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