Preferential concentration due to turbulence in a particle-laden jet flow.

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Introduction

- Volcanic Ash Transport and Dispersion (VATD) is a hazard that poses a significant threat to human life and infrastructure.
- Volcanic ash can reach up to 50km into the atmosphere and can remain airborne for weeks, traveling thousands of miles before settling.

Figure: The plume of the eruption of Mount St. Helens on 18 May 1980 spread 10 to 11 kilometers, attaining heights of 22 to 23 kilometers.
Source: Taylor, The Eruption of Mount St. Helens in 1980, May 18, 2015, The Atlantic.

- Ash particles collide with each other and form larger aggregates that dictate the atmospheric residence duration and areal coverage of volcanic plumes.
- Ash aggregation was studied previously on particle laden jet flow by collecting aggregates on microscope slides for different Stokes number ranging from 1.0 to 9.4, Reynolds numbers ranging from 5500 to 11000, and mass loadings ranging from 1 to 3 percent.
- Preferential concentrations due to turbulence, also called clusters, can promote ash aggregation by increasing the probability of collision among the ash particles.
- Preferential concentrations have been studied in different applications, such as analyzing localized concentrations of fuel in combustion and processing minerals.
- A similar method has been adopted here to analyze preferential concentration in particle-laden flow in the study of ash aggregation in volcanic plumes.

Research Objective

To find out relative quantitative comparison of preferential concentration in particle laden flow for different Stokes number, Reynolds number, relative humidity, and mass loading.

Experimental Setup

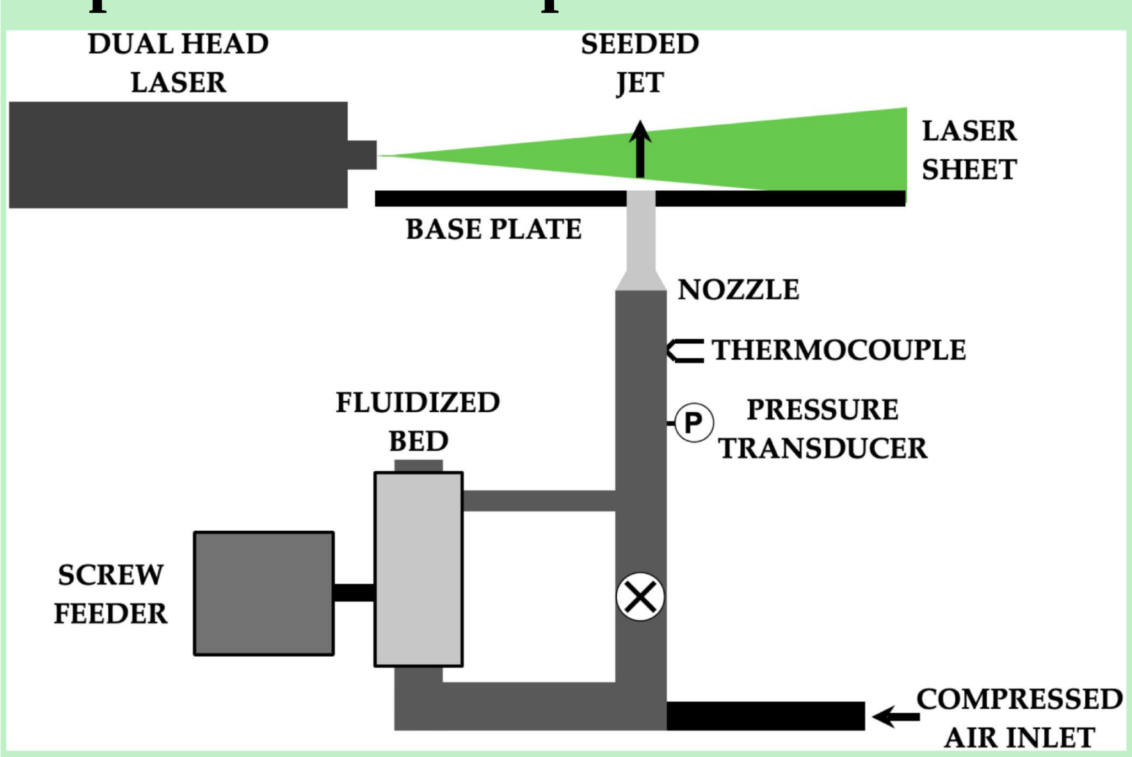


Figure: Diagram of jet apparatus.

- A volumetric screw feeder from Schenck Process LLC is utilized to feed particles into the flow at a well-controlled rate.
- The fluidized bed evenly distribute particle into the flow.
- Air is supplied from a compressed air source through the fluidized bed, exits the nozzle at consistent velocity.
- A dual head LASER emits LASER sheet at the center of the air jet.
- A camera captures image of the jet from the orthogonal angle of the LASER sheet.
- A synchronizer controls the LASER and the camera to facilitate synchronized operation of the equipment together.

Test Parameters

- Reynolds number (Re) : The relative importance of inertial forces to viscous forces in a given flow. $Re = \rho dV/\mu$.
  Reynolds number is the measure of the turbulence in the jet and the particle collision rate depends on it.
- Relative humidity (RH) : The fraction of actual water vapor density (ρ_v) to the saturation vapor density ($\rho_{v,sat}$) at the given conditions: $RH = (\rho_v / \rho_{v,sat}) * 100\%$
  Water provides a method to stick particle together, thus at higher relative humidity, it is expected to observe more aggregation.
- The Stokes number (St) : The ratio of the particle response time (τ_p) to the characteristic time scale of the fluid (τ_f). $St = \tau_p / \tau_f$. Stokes number is strongly related to turbulent flow structures in jet flow, thus influence preferential concentration in a particle-laden jet flow.
- Mass loading (Φ): The ratio of the particle mass flow rate (mp) to the fluid mass flow rate (mf): $\Phi = mp / mf$. At higher mass loading levels, an increased presence of particles is anticipated, thereby facilitating more preferential concentration.

Clustering Analysis

- A series of images were captured under specific test conditions in a particle-laden flow.
- An average image was generated by taking the mean value of each pixel for all the instantaneous images.
- Cluster maps were created by subtracting the instantaneous image from the average image to identify clusters.
- A smoothness filter was applied to minimize noise and an area threshold was applied to subtracted image to get rid of the areas that are too small to be counted as clusters.
- Cluster slices were generated by multiplying the cluster map with the original instantaneous images.

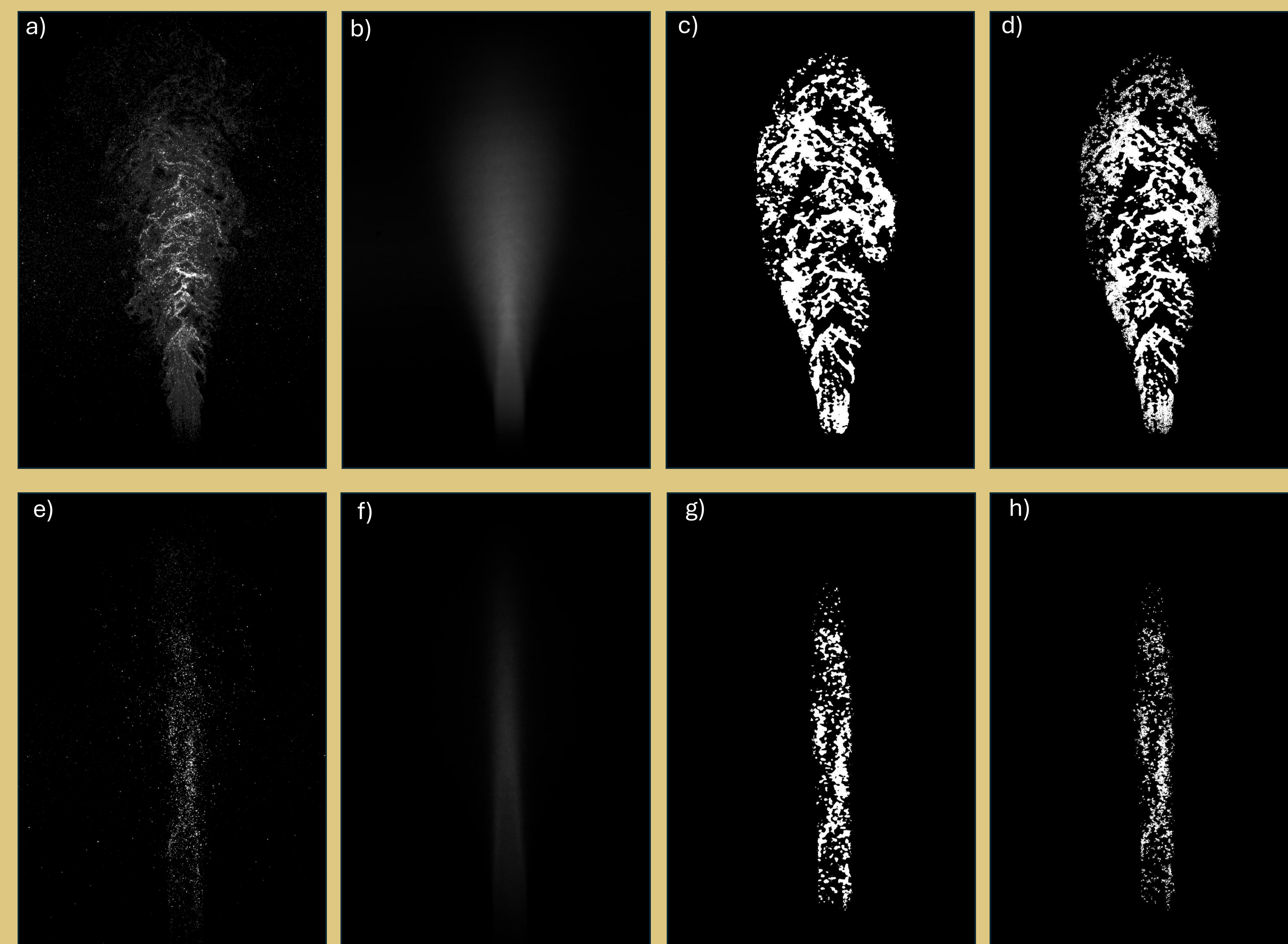
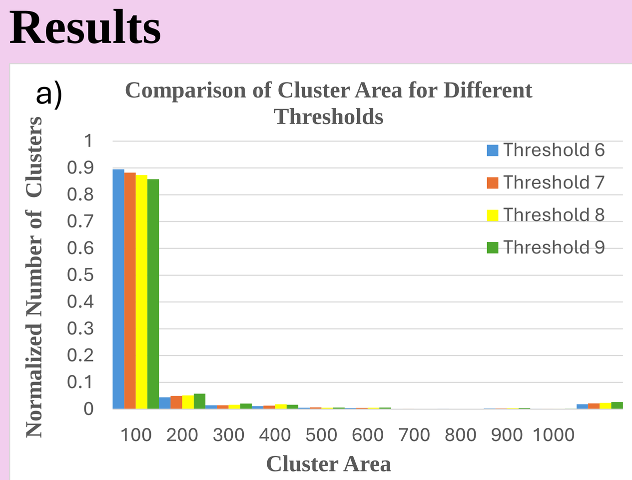
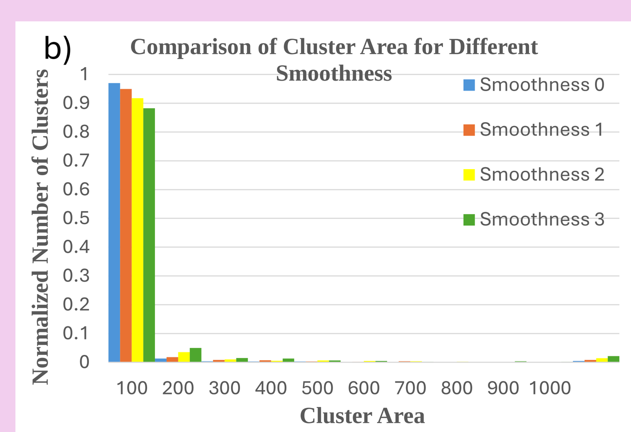
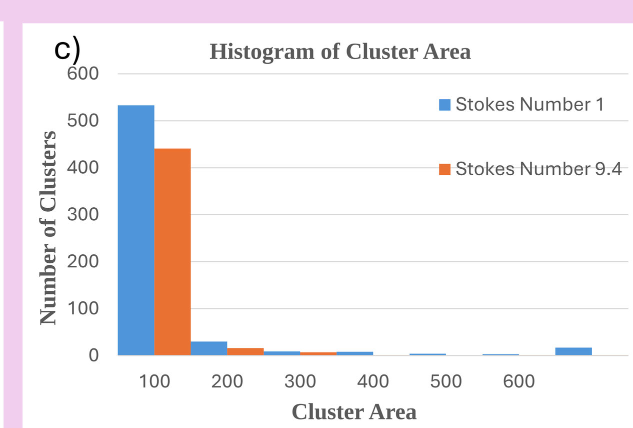


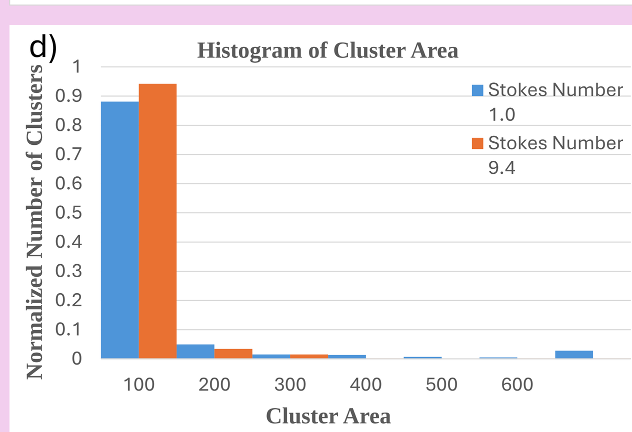
Figure: a) instantaneous image, b) average image, c) cluster map, and d) cluster slice for a test run with hollow glass particles. e) instantaneous image, f) average image, g) cluster map, and h) cluster slice for a test run with nickel particles.

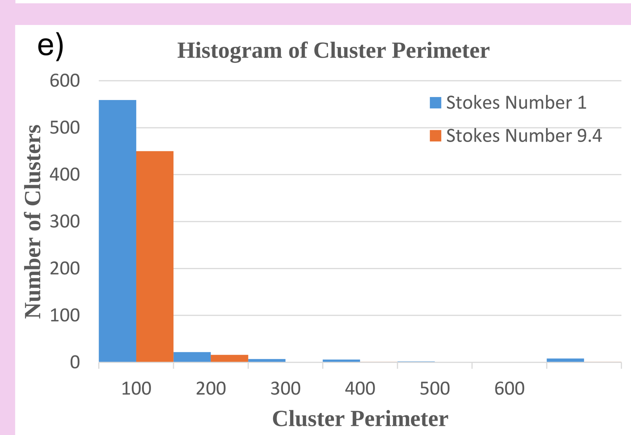
Results

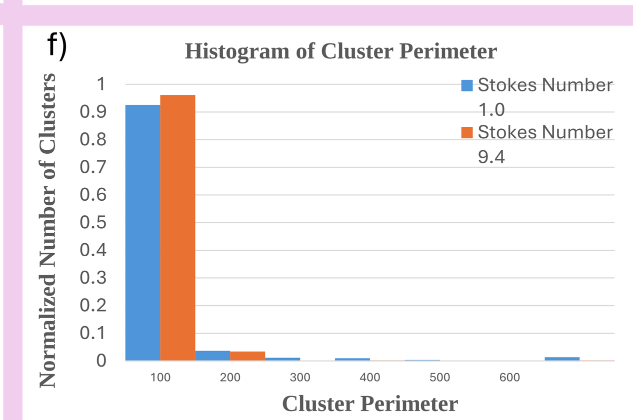


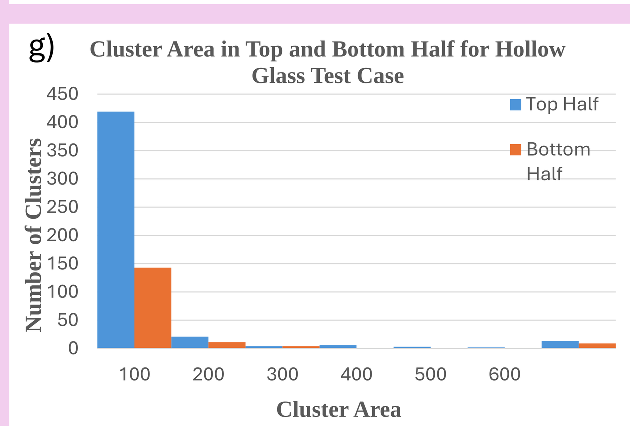


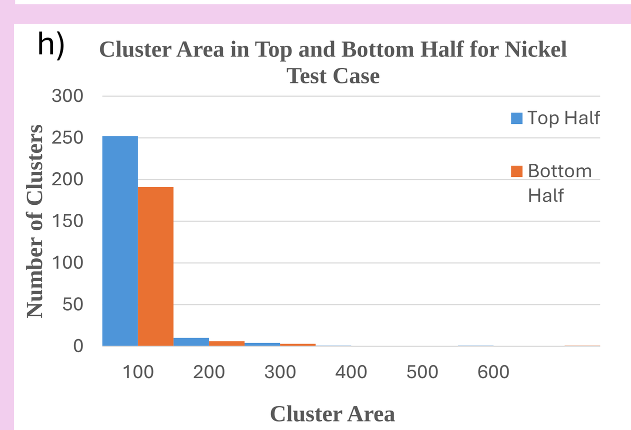


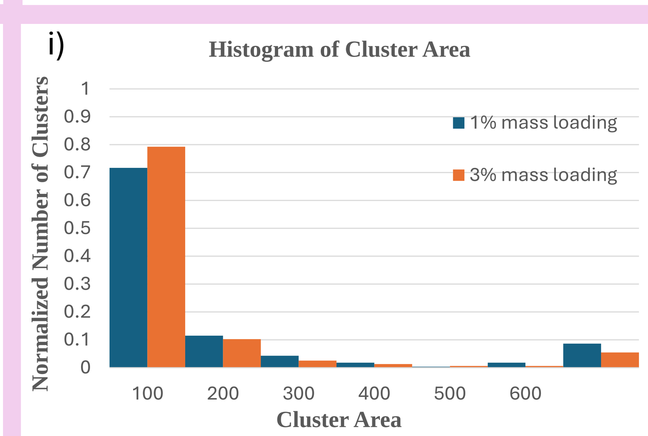


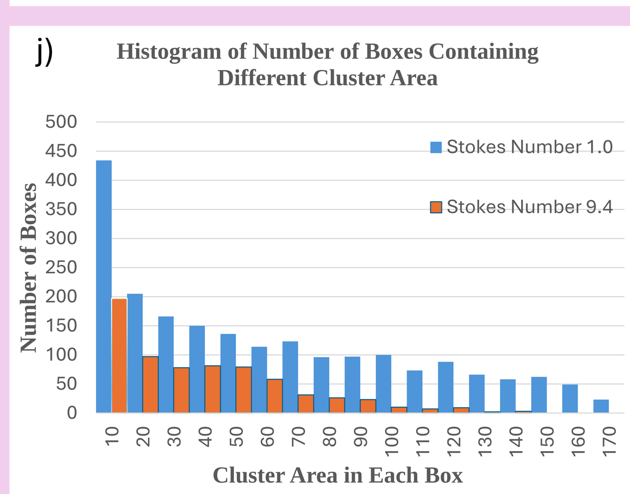












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Particle Type	Mean Diameter (μm)	Relative Humidity (RH)	Reynolds Number (Re)	Stokes Number(St)	Mass Loading (%)	Number of Clusters	Average Area of Clusters (mm2)	Total Area of Clusters	Camera-Laser Settings
Hollow Glass	13.25	40%	5500	1	1	622	0.20	125	Setting 1
Hollow Glass	13.25	60%	5500	1	1	279	1.43	399	Setting 2
Hollow Glass	13.25	80%	5500	1	1	1054	0.13	137	Setting 1
Hollow Glass	13.25	40%	5500	1	3	313	1.72	538	Setting 2
Hollow Glass	13.25	60%	11000	2.1	1	1047	0.33	346	Setting 1
Nickel	13.87	40%	5500	9.4	1	200	0.05	11	Setting 1
Nickel	13.87	60%	5500	9.4	1	142	0.73	104	Setting 2
Nickel	13.87	75%	5500	9.4	2	452	0.18	82	Setting 1

Images Taken with Two Settings

The number of clusters and cluster area found from this analysis greatly depends on the test condition, such as the focal point of camera, presence of fog and the amount of light from the LASER. Test runs were conducted in two settings, and the results were significantly different. However, with both settings, the comparison of different cases were observed similar.

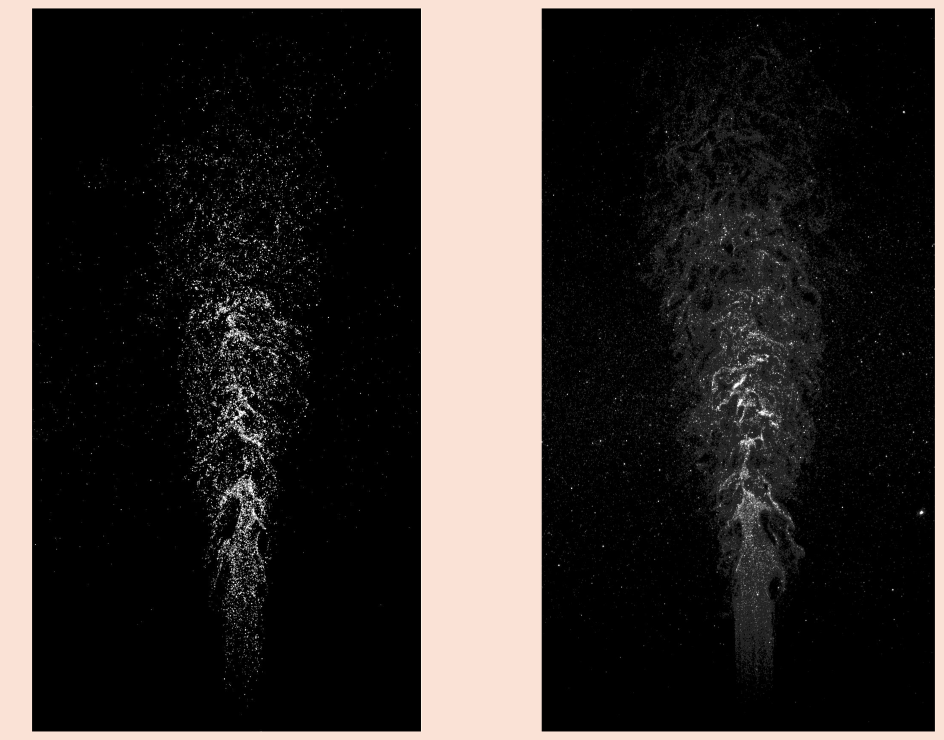

Figure: Images with two different camera focal point settings.

Discussion

- Area threshold was applied in the subtracted images so that the areas that are too small to be considered as clusters can be ignored.
- The Gaussian smoothness filter was applied in the instantaneous images to reduce noise. All these tools have no significant effect while comparing clusters among different test cases.
- The number of clusters are observed around 2 to 3 times higher for a hollow glass particle test run with Stokes number of 1.0 than a nickel test run with Stokes number of 9.4.
- Total cluster area was observed around 3 to 10 times higher for a hollow glass particle test run with Stokes number of 1.0 than a nickel test run with Stokes number of 9.4.
- No significant change is observed for different relative humidity in the test run with hollow glass. However, with nickel particles, cluster area was found 8 times higher in 75% relative humidity than in 40% relative humidity.
- For both hollow glass and nickel test runs, it has been observed that the clusters are likely to be formed more at the top half of the flow area. In lower Stokes number this trend is more prevalent than in higher Stokes number.
- With a higher mass loading both the cluster areas and the number of the clusters found higher for both hollow glass and nickel test run.
- Difficulties were encountered by the test apparatus in achieving consistent and reproducible particle loadings under the designated conditions. The fluidized bed exhibited struggles in picking up the particles at lower Reynolds numbers, which led to as much as 75% of the dispensed mass being retained inside the bed.
- The measurement accuracy of particle mass was compromised when dispensing particles in the range of approximately 3-10 grams. An inherent uncertainty
- of ±1 gram in the weighing scale used contributed to a total propagated uncertainty of ±2 grams, culminating in a maximum relative uncertainty of up to 66% for the smallest mass measurements.
- It's important to compare test runs in the same camera-Laser setting because it helps eliminate factors that could skew the results.

Conclusion

- Significant difference is observed on clustering for test runs of different Stokes numbers.
- Some influence was observed with different Reynolds number, but these are not varied independently of Stokes number.
- It is needed to run more test cases to compare clustering for varying relative humidity and Reynolds number.

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