Evaluation of Spouted Bed Flow Instabilities via High Speed Video and Pressure Fluctuations.

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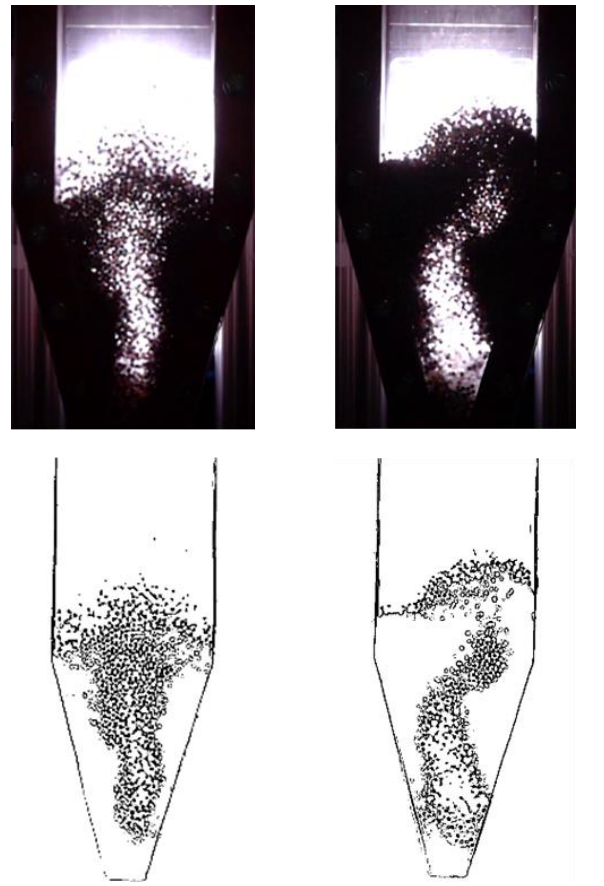
Introduction

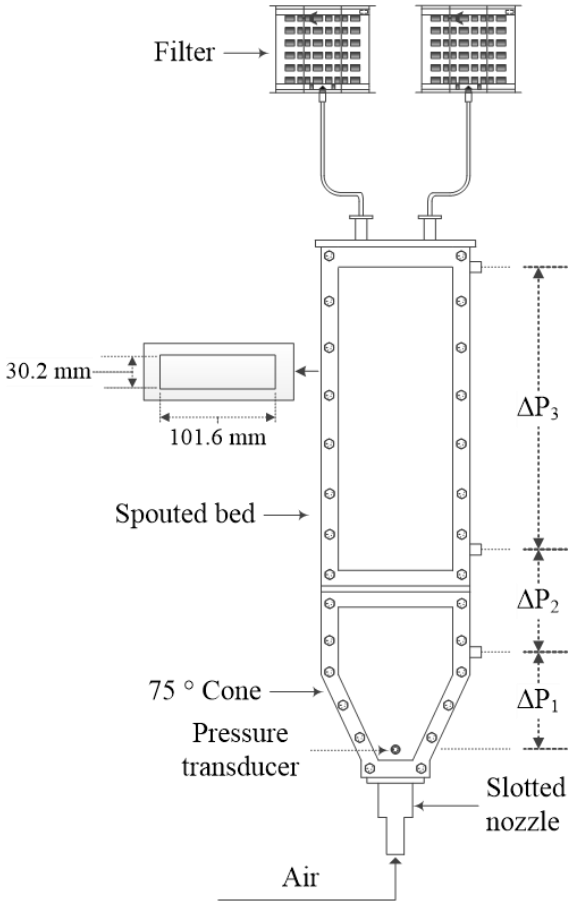
- **Slot-rectangular spouted beds are often used in drying and coating of Geldart D materials.**
  - easy to scale up, can achieve different flow regimes via changing inlet nozzle.
- **The majority of previous spouted bed literature has focused on cylindrical spouted beds, not slot-rectangular.**
- **The limited amount of slot-rectangular literature has noted the existence of flow/spout instabilities.**
  - Asymmetric gas core, pulsations, oscillation between spouting and slugging.
- **Dogan et al. determined that these were actually separate spouting regimes with different flow characteristics.**

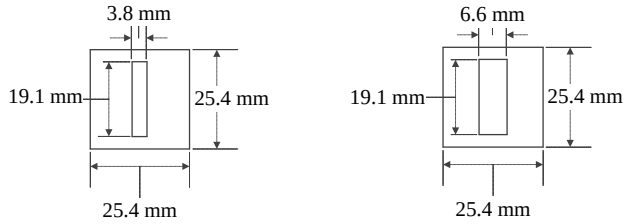
The objective of the current study was to examine these spouting instabilities in a laboratory-scale slot-rectangular spouted bed via a combination of high speed video and analysis of pressure signals for a variety of initial static bed heights and inlet nozzle sizes.

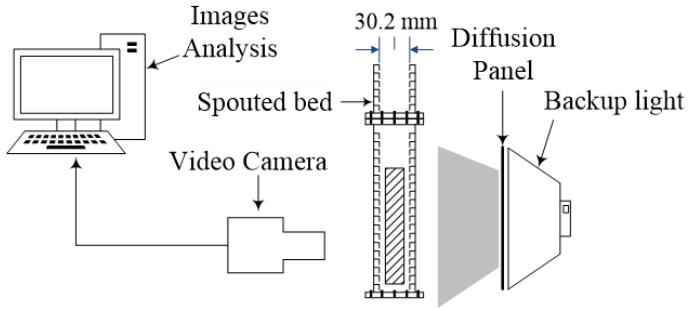


Symmetric Spouting Asymmetric Spouting

Experimental Setup

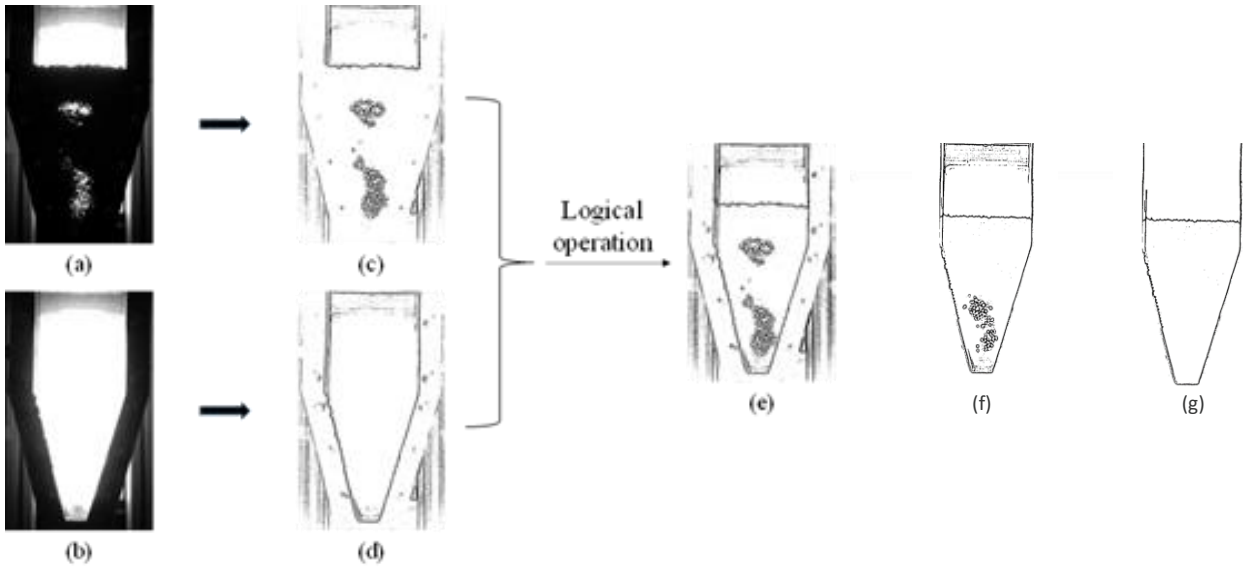


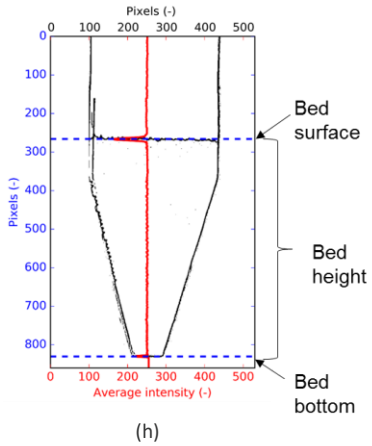




- **Slot-Rectangular Spouted Bed:**
  - Width: 101.6mm (4 inches)
  - Depth*: 30.2mm (1 3/16 inches)
  - Height: 864mm (34 inches)
  - Aluminum Frame with clear acrylic panels.
- **3D Printed Nozzle Assemblies**
  - 3/8-inch equivalent (3.8mm x 19.1mm)
  - 1/2-inch equivalent (6.6mm x 19.1mm)
- **Sony RX10-II Camera**
  - 500 fps
  - 1920 x 1080 pixels
  - 0.001s shutter time
- **Dracast LED500 light panel.**
- **3.2mm Nylon Beads**
  - SG: 1.13
  - U_{mf} = 1.08 m/s

Video Analysis: Determination of Bed Height



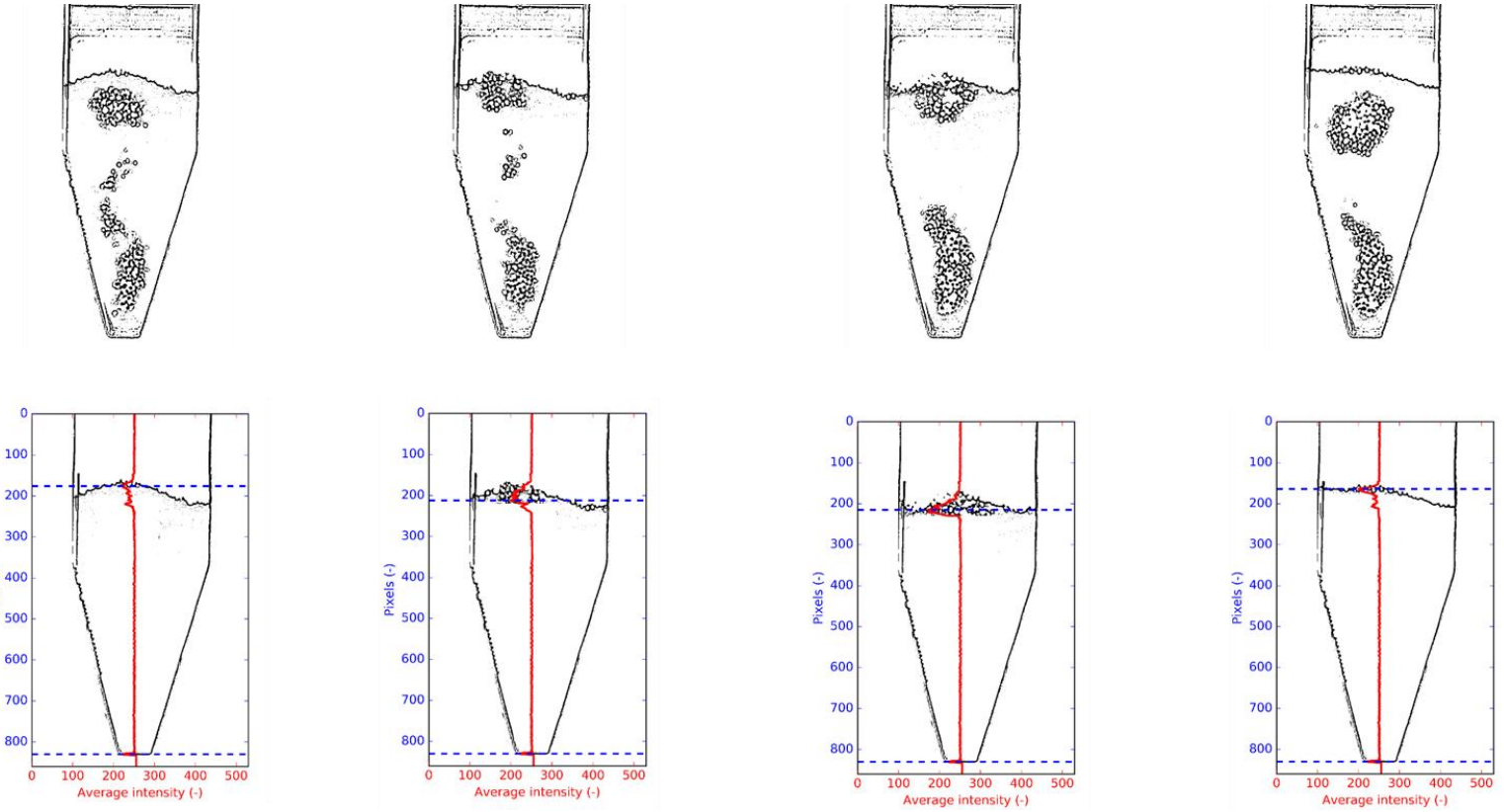


(h)

Analysis procedure:

- Acquire "blank" video (b)
- Acquire video of test condition (a)
- Convert (a) and (b) to greyscale (c) and (d)
- Merge (c) and (d) and convert to binary (e).
- Crop (e) to isolate the bed image, generating (f).
- Create "extracted binary" (g) by deleting all information except bed surface and bottom from (f).
- Calculate and plot average pixel intensity (h)
  - Bed bottom and surface correspond to peak pixel intensities.

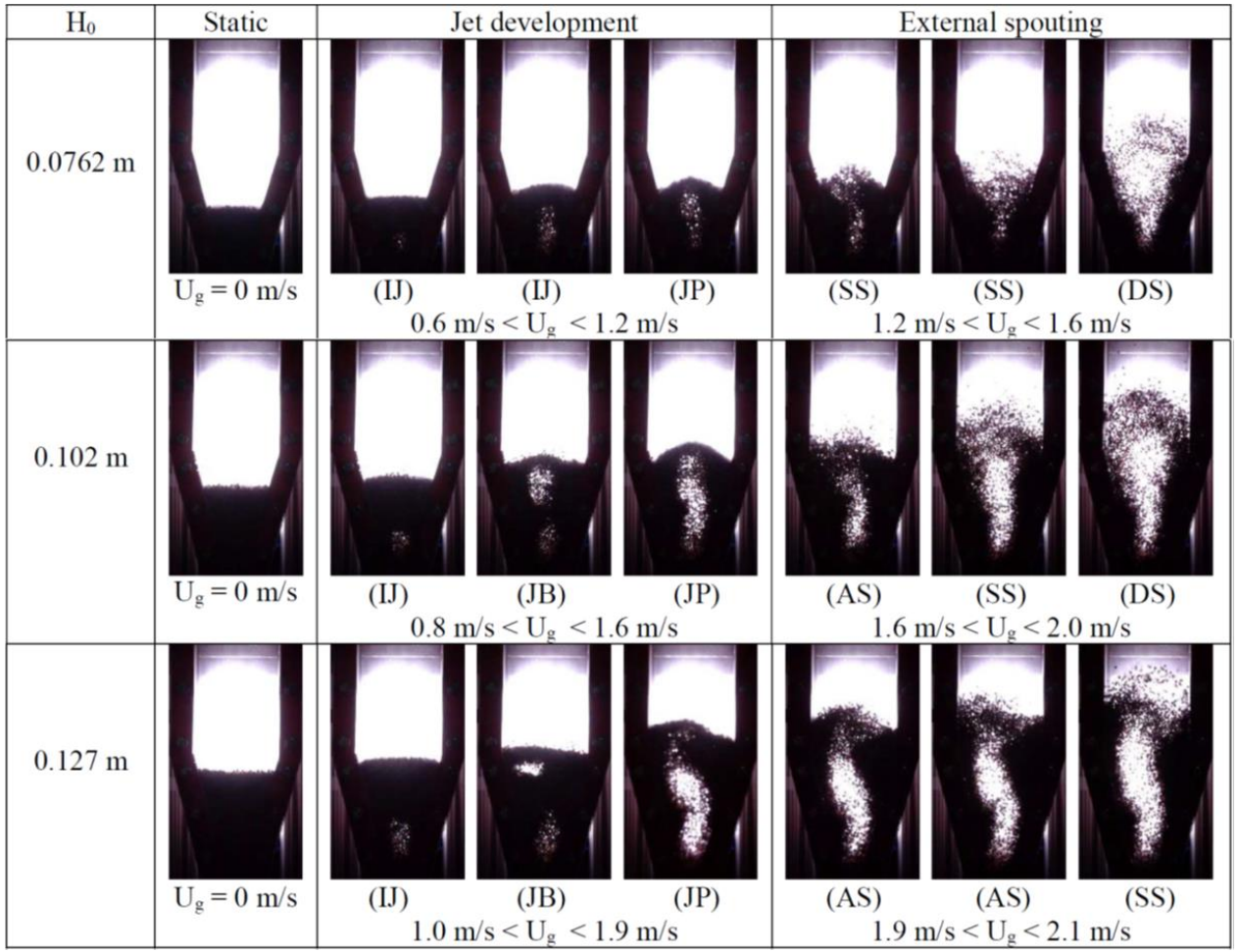
Video Analysis: Sample Results



Observed Spouting Regimes/Behaviors

- **Internal Spouting Zone ($U_{ms} < U_g < U_{ex}$)**
  - **Internal Jet:** Initial formation of a gas void (or cavity) at the bottom of bed, which then expands upwards through the bed.
  - **Jet-Bubbling:** Exhibits a pattern where the jet periodically expands upwards until a portion of the jet detaches and forms a bubble that continues to rise upwards through the bed, while the remainder of the jet collapses to a lower height prior to renewed expansion leading to the formation of the next bubble.
  - **Jet Pulsating:** similar to Jet-Bubbling, but the jet penetrates much of the bed height, and bubbles form close to bed surface, eject significant amounts of solids into the freeboard region. Unlike in the case of jet-bubbling, the jet itself does not undergo significant expansion and collapse.
- **External Spouting ($U_g >= U_{ex}$)**
  - **Symmetric Spouting:** Jet completely penetrates the bed, is axially aligned, exhibits "fountain" structure. Stable with no pulsations.
  - **Asymmetric Spouting:** Jet is not axially-symmetric. Can be skewed to one side of the bed, or curved (snake-like) with triangular-shaped stagnant zones.
  - **Dilute Spouting:** Annulus appears to have the same particle concentration as the spout.
  - **Incoherent Spouting:** Exhibits extreme pulsations, with periodic solids entrainment, recirculation and fountain height fluctuations.

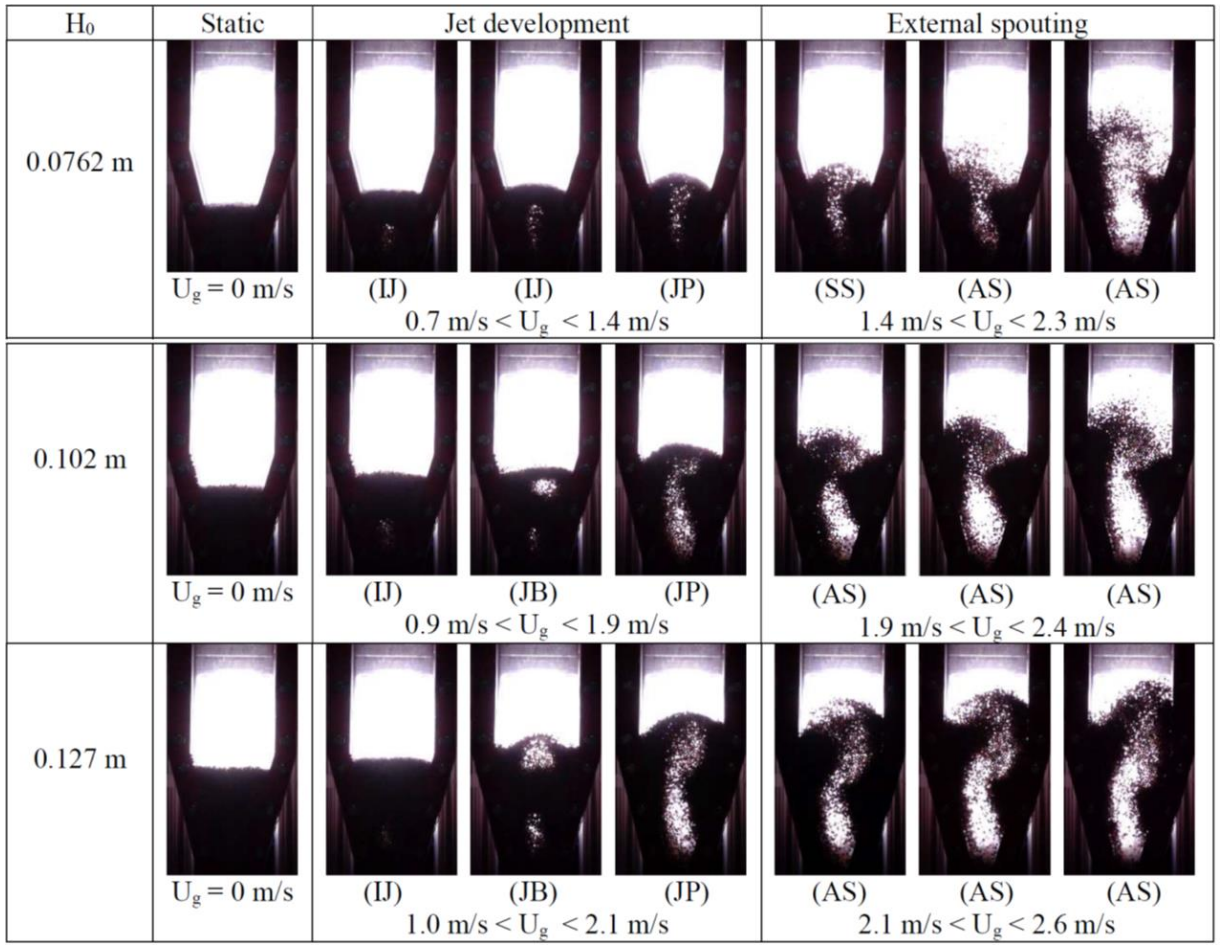
Visual Analysis of Spout Stability



(source: Yang et al., Determination of flow patterns by image analysis in a rectangular spouted bed, submitted to Powder Tech)

- **Images show progression from static bed through external spouting regimes for 3/8-in equivalent rectangular nozzle.**
- **Jet development (internal spouting) regions dominated by:**
  - 3-in and 4-in bed: Jet-bubbling
  - 5-in bed: Jet-pulsating
- **External spouting regions dominated by:**
  - 3-in bed: symmetric spouting transitioning to dilute spouting.
  - 4-in bed: recoverable asymmetric – symmetric-dilute spouting
  - 5-in bed: recoverable asymmetric – symmetric spouting

Visual Analysis of Spout Stability



(source: Yang et al., Determination of flow patterns by image analysis in a rectangular spouted bed, submitted to Powder Tech)

- **Images show progression from static bed through external spouting regimes for 1/2-in equivalent rectangular nozzle.**
- **Jet development (internal spouting) regions dominated by:**
  - 3- , 4-, and 5-in beds: Jet-bubbling
- **External spouting regions dominated by:**
  - 3- , 4-, and 5-in beds: asymmetric spouting

Jet-Bubbling vs Jet Pulsating

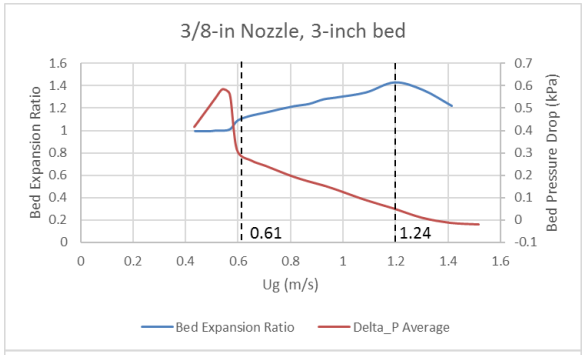
Jet-bubbling regime

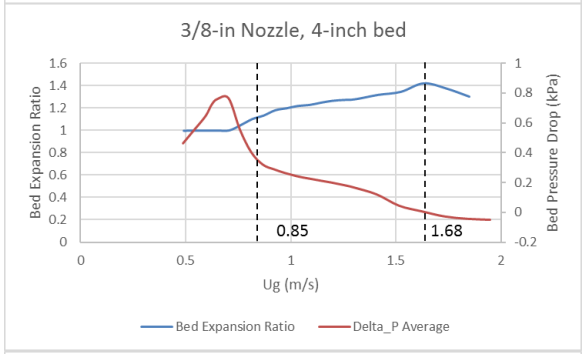
Jet-pulsating regime

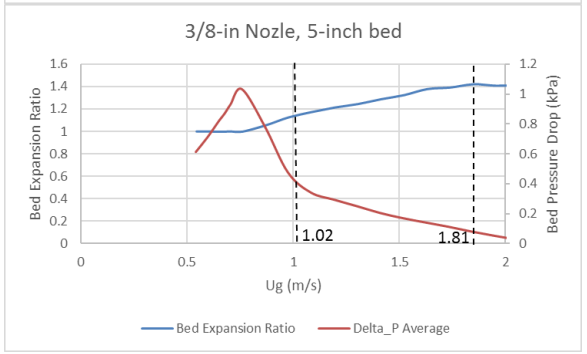
- **Jet-bubbling:**
  - Jet expands upwards towards the surface of the bed.
  - As it approaches the bed surface, the upper portion of the jet detaches and forms a bubble.
  - These extreme variations in jet height result in larger pressure fluctuations.
- **Jet-pulsating:**
  - Jet is mostly uniform in height.
  - Bubbles that are formed are smaller and detach from the very top of the jet.
  - Leads to smaller fluctuations in pressure.

Regime Mapping

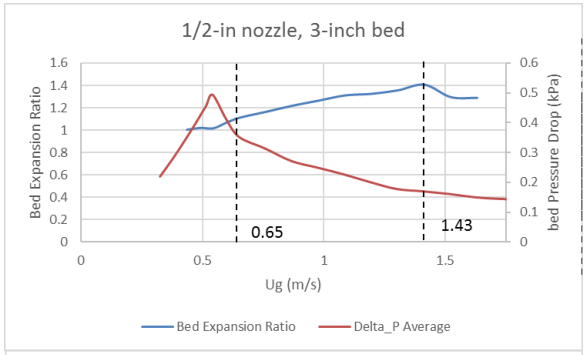
3/8-inch-Equivalent Rectangular Nozzle

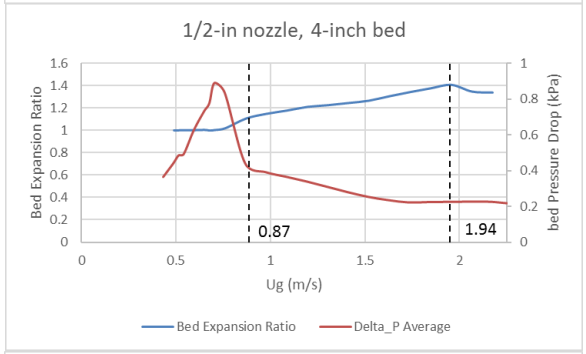


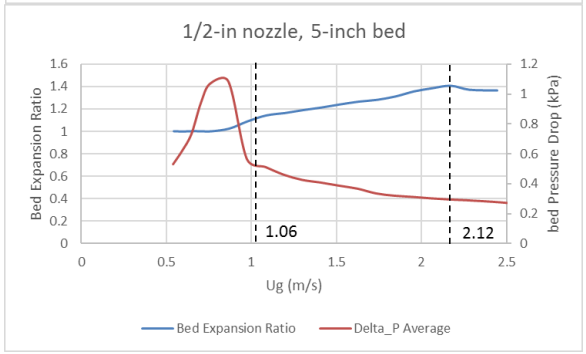




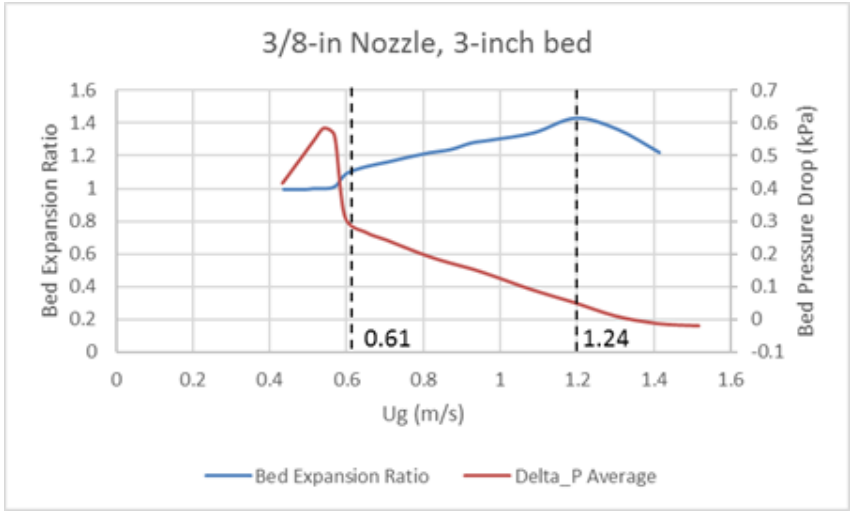
1/2-inch-Equivalent Rectangular Nozzle





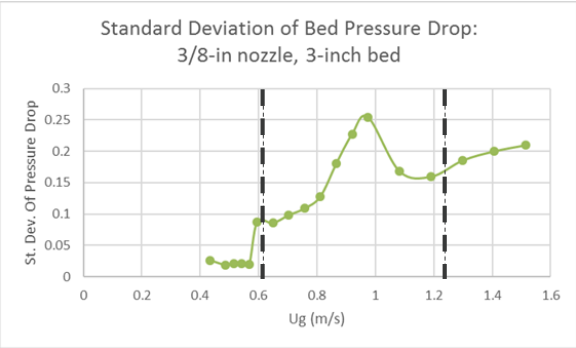


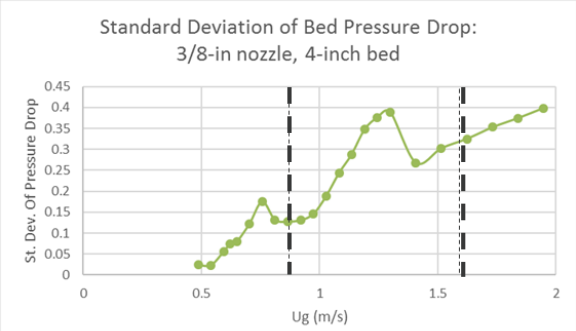
- **Minimum (internal) spouting velocity obtained from average pressure drop profiles.**
- **External spouting velocity determined from bed expansion ratio (HSV analysis)**
- **In each case, $U_{ex} \approx 1.4$**
- **In most cases, $U_{ex} \approx 2*U_{ms}$**
- For the two 5” static bed height cases:
  - **$U_{ms} \approx U_{mf}$** (U_{mf} = 1.08 m/s)

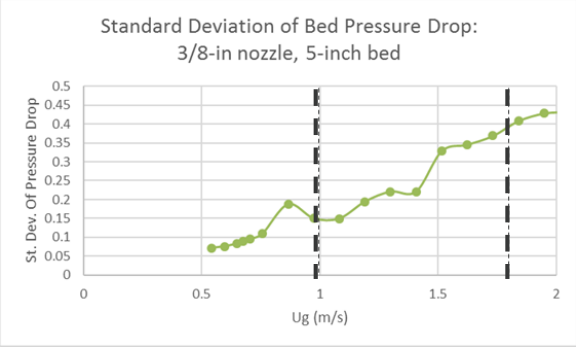


Standard Deviation of Bed Pressure Drop

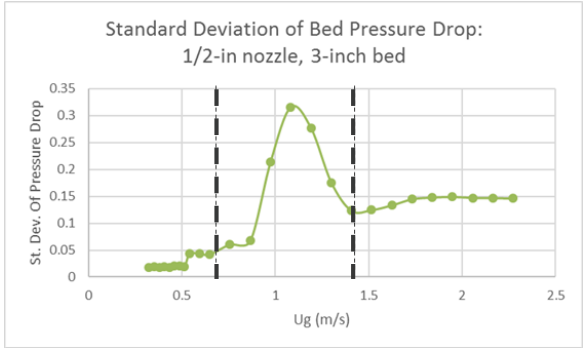
3/8-inch-Equivalent Rectangular Nozzle

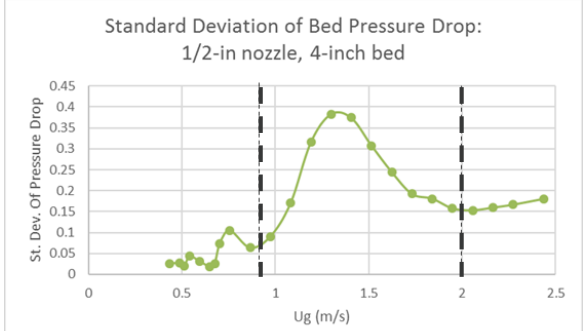


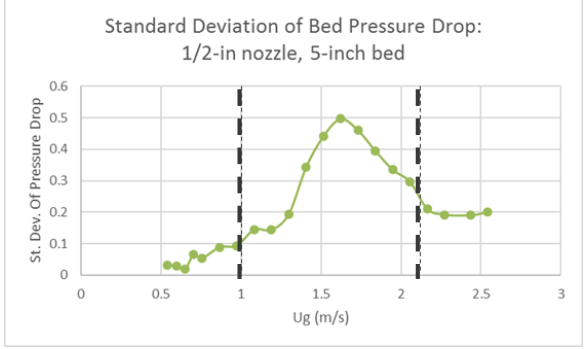




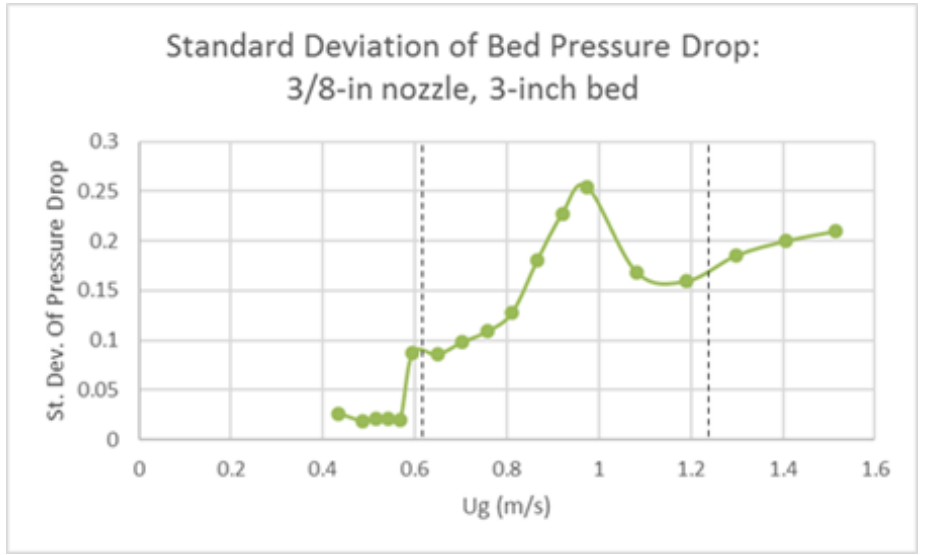
1/2-inch-Equivalent Rectangular Nozzle







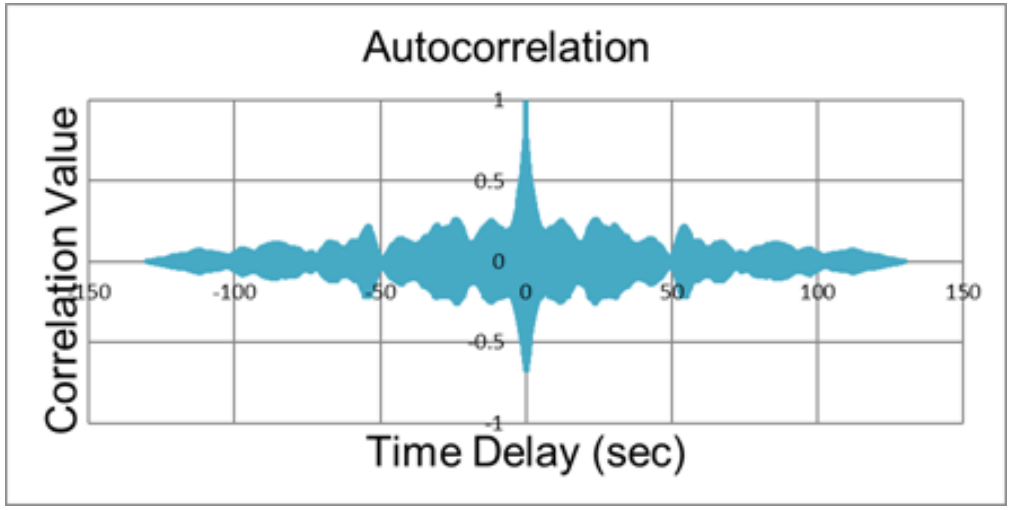
- **In all but the 3/8-in nozzle, 5-in bed case, the area bounded by the dotted lines contains a "hump"**
  - Coincides with the jet-bubbling regime
  - Caused by fluctuations of the jet height due to detaching of bubbles.
- **The 3/8-in nozzle, 5-in bed case lacks the "hump"**
  - Coincides with jet-pulsating regime.
- **Larger "humps" associated with asymmetric spouting suggest that more vigorous bubbling leads to flow asymmetries.**



Autocorrelation Data

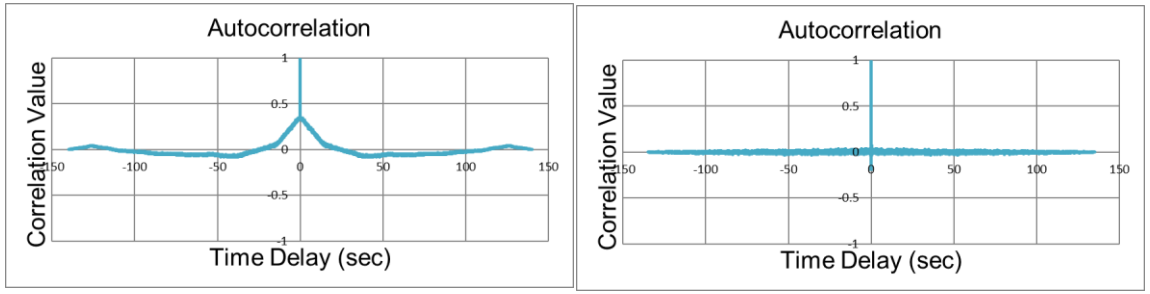
- **Autocorrelation function of a signal:**
  - Correlation between two points within a signal separated by a time lag.
  - If the signal is period, the autocorrelation will be periodic.
  - Function is additive. (if signal has multiple periodicities, so will the autocorrelation)
  - Given by:

$$c_{xx}(k) = \sum_{n=0}^{N-|k|-1} (x(n) - \bar{x})(x(n-k) - \bar{x})$$



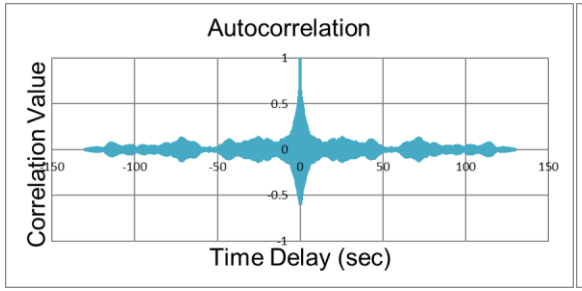
Autocorrelation Data

3/8"-equivalent nozzle, 3 inch (0.0762 m) Static Bed

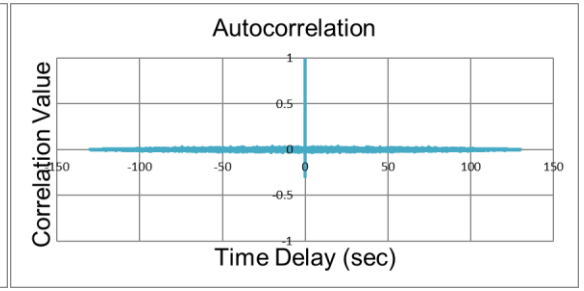


0.44 - 0.57 m/s

0.65 – 0.81 m/s



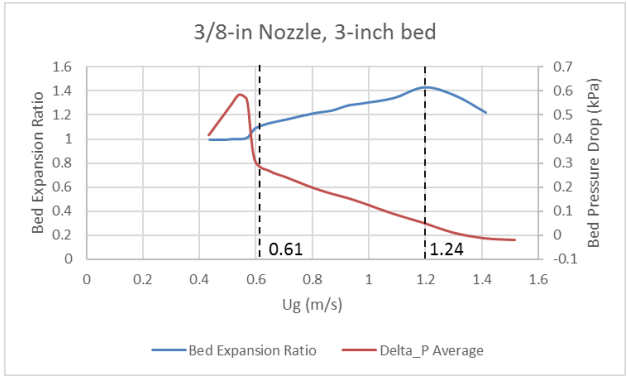
0.87 – 1.2 m/s



1.31 – 1.63 m/s

- **The region bounded by U_{ms} and U_{bx} exhibits two separate waveforms in the autocorrelation data.**
  - The first is assumed to be associated with formation of the initial gas jet.
  - The second is believed to be associated with formation of bubbles within the dense bed (i.e. the jet-bubbling regime).

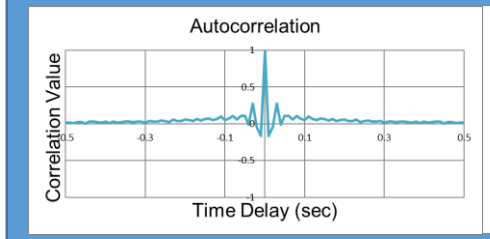
H_0	Static	Jet development			External spouting		
0.0762 m							
	$U_g = 0$ m/s	(IJ)	(IJ)	(JP)	(SS)	(SS)	(DS)
		0.6 m/s < U_g < 1.2 m/s			1.2 m/s < U_g < 1.6 m/s		



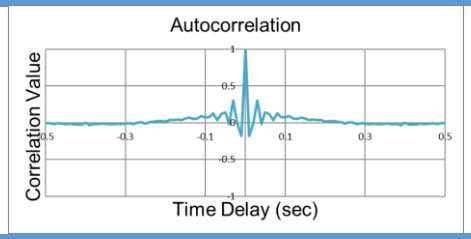
Autocorrelation in Jet Development Region

3/8”-equivalent nozzle, 3 inch (0.0762 m) Static Bed

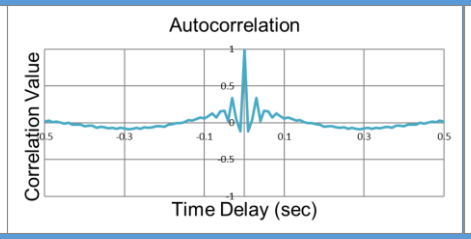
Internal Jet Development



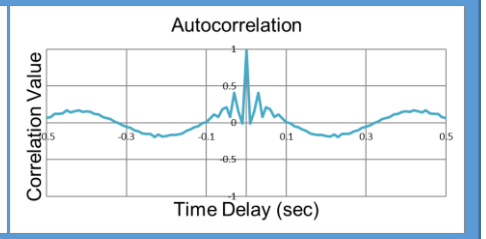
0.652 m/s



0.707 m/s

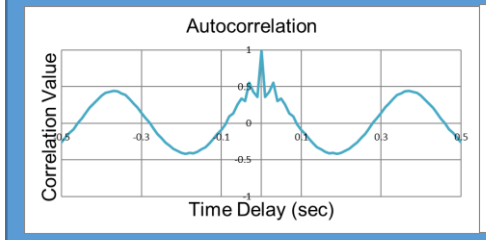


0.761 m/s

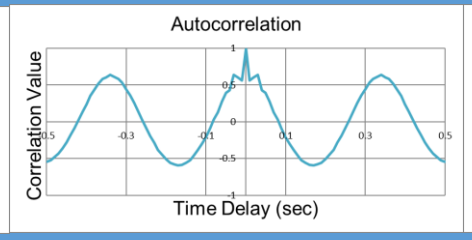


0.816 m/s

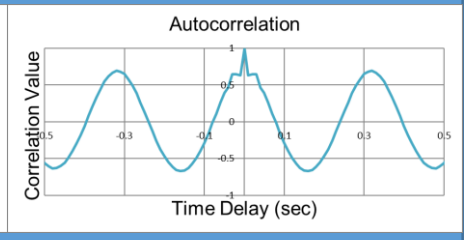
Bubble Formation



0.870 m/s

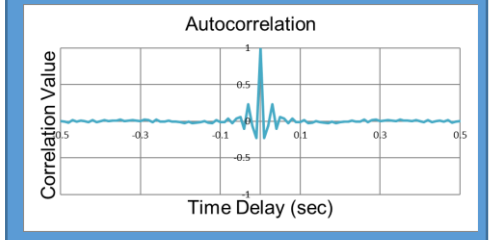


0.925 m/s



1.088 m/s

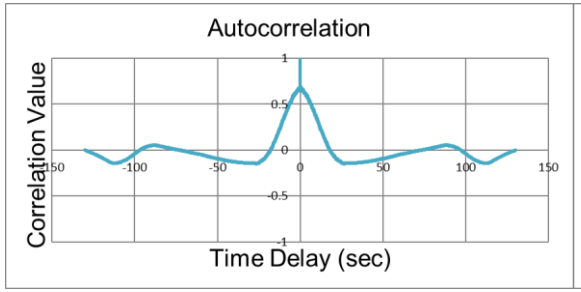
External Spout



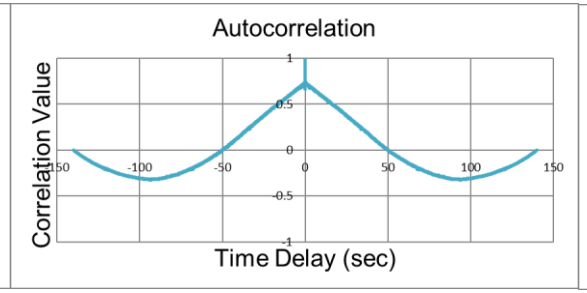
1.305 m/s

Autocorrelation Data

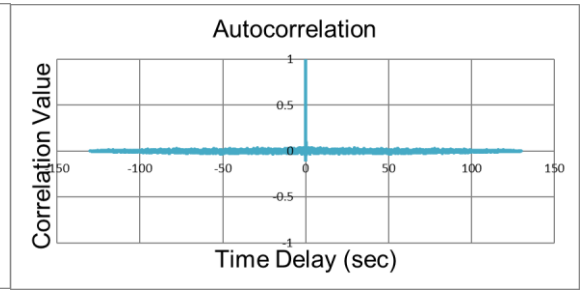
3/8”-equivalent nozzle, 4 inch (0.102 m) Static Bed



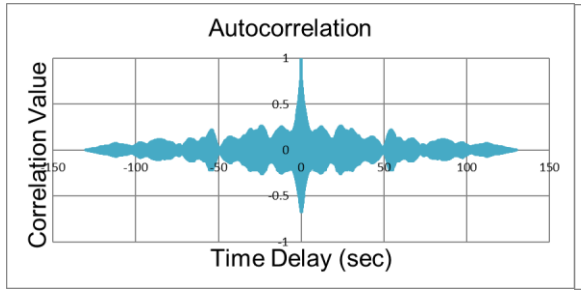
0.49 – 0.71 m/s



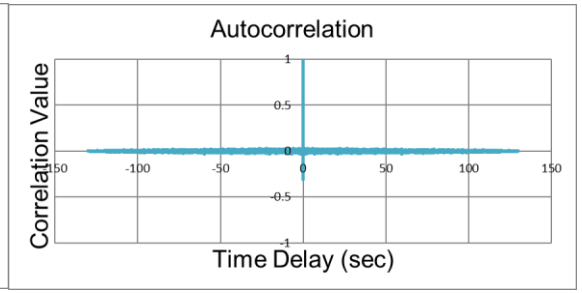
0.76 - 0.87 m/s



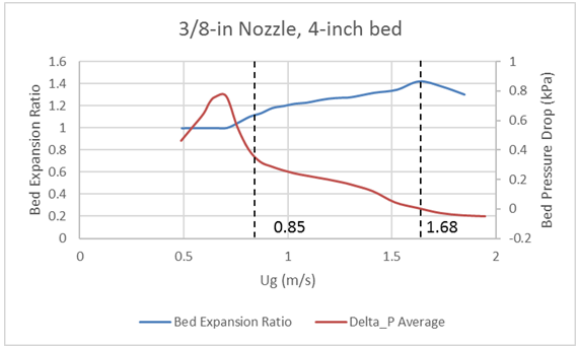
0.93 – 1. 03 m/s

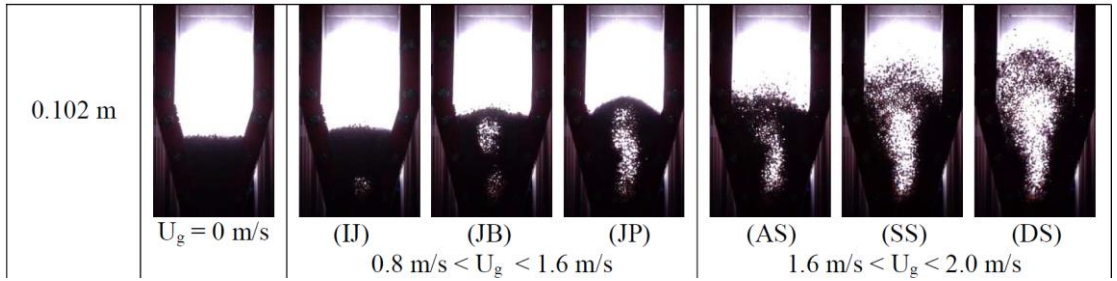


1.09 - 1.52 m/s



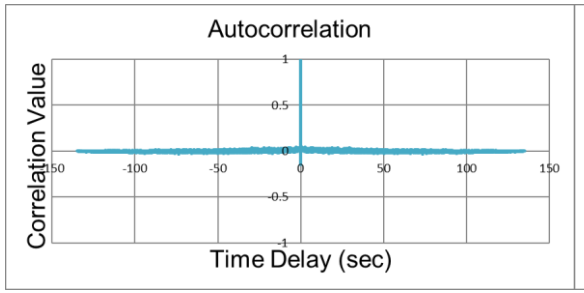
1.63 – 2.0 m/s



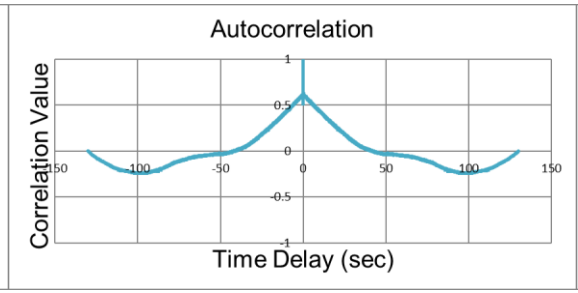


Autocorrelation Data

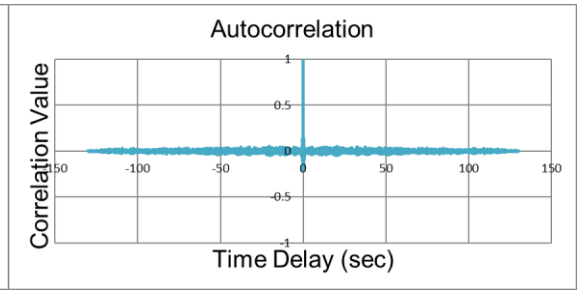
3/8”-equivalent nozzle, 5 inch (0.127 m) Static Bed



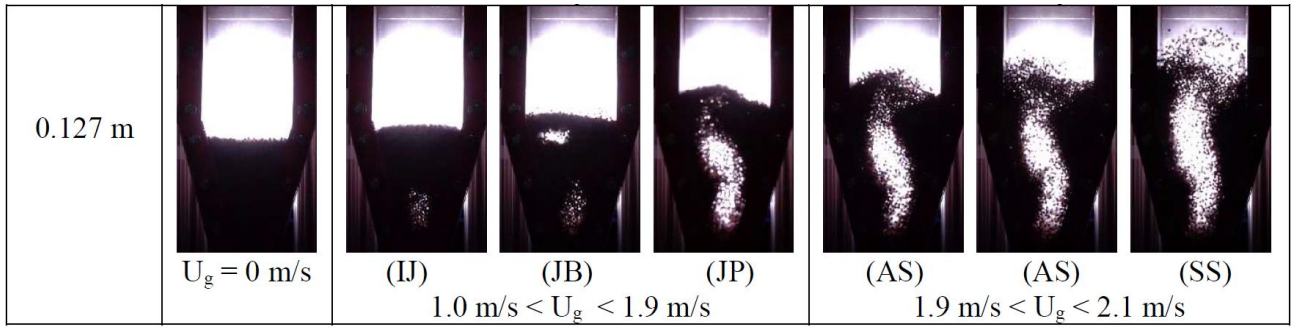
0.54 - 0.87 m/s

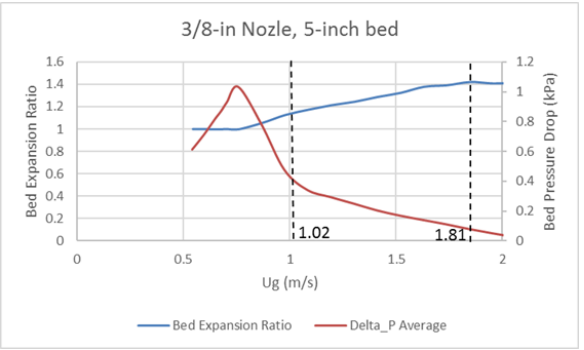


0.979 m/s



1.08 – 2.07 m/s



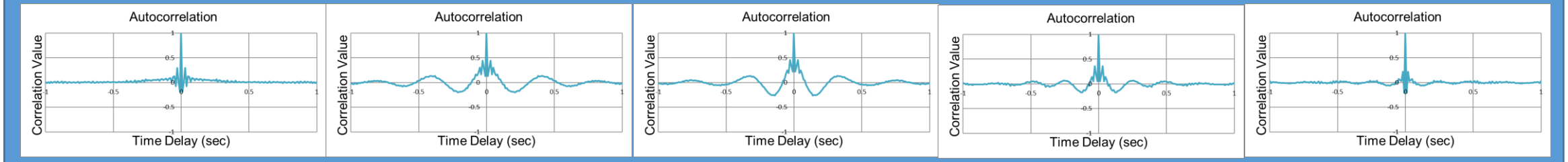


Autocorrelation in Jet Development Region

3/8"-equivalent nozzle, 5 inch (0.127 m) Static Bed

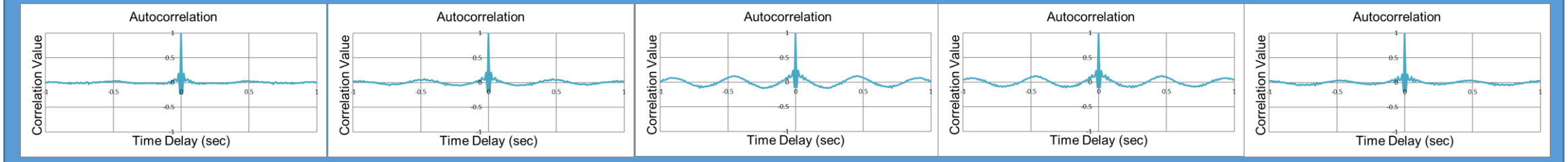
NATIONAL ENERGY TECHNOLOGY LABORATORY

Internal Jet Development



1.197 m/s | 1.305 m/s | 1.414 m/s | 1.523 m/s | 1.632 m/s

Jet Pulsating

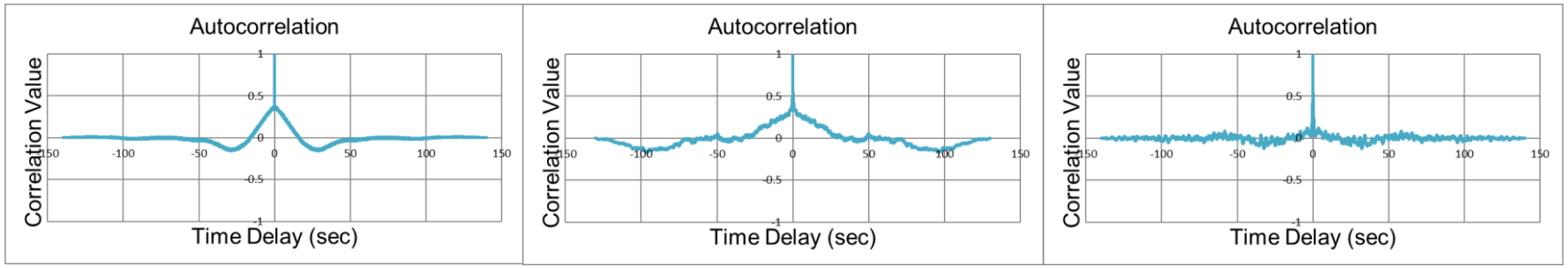


1.740 m/s | 1.849 m/s | 1.958 m/s | 2.067 m/s | 2.175 m/s

This bed height exhibits a transition from jet formation to jet-pulsating flow as opposed to jet-bubbling, as evidenced by the lack of a strongly correlated, period pressure signal.

Autocorrelation Data

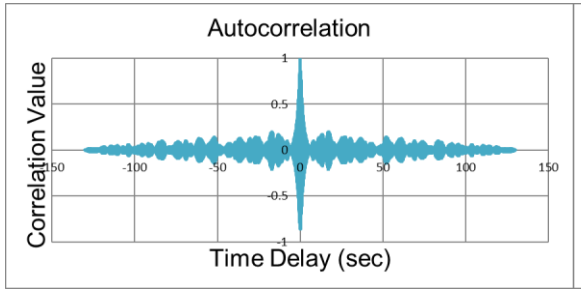
1/2”-equivalent nozzle, 3 inch (0.0762 m) Static Bed



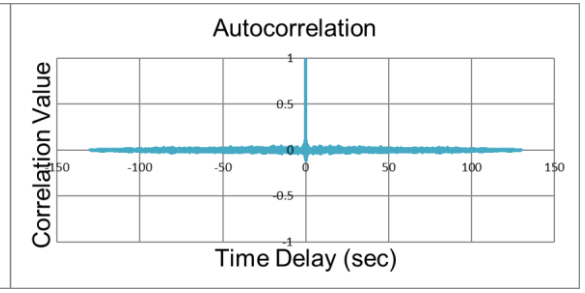
0.27 – 0.51 m/s

0.54 – 0.60 m/s

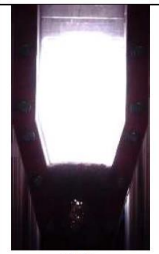
0.65 – 0.87 m/s

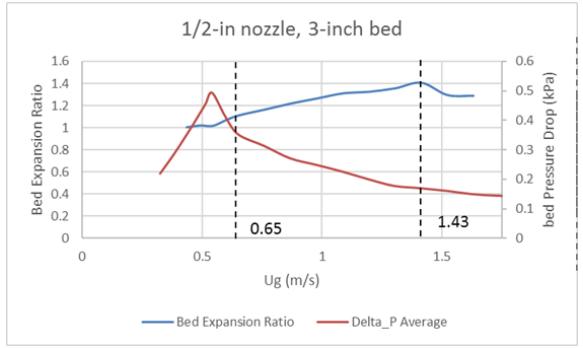


0.98 – 1.41 m/s



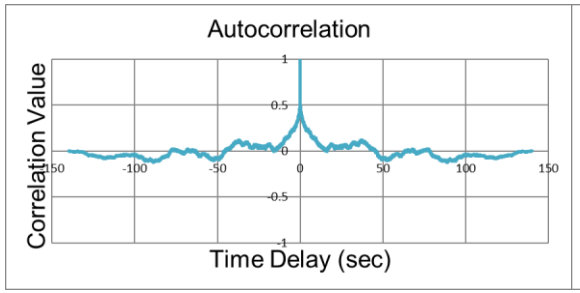
1.52 – 2.3 m/s

H_0	Static	Jet development			External spouting		
0.0762 m							
	$U_g = 0$ m/s	(IJ)	(IJ)	(JP)	(SS)	(AS)	(AS)
		0.7 m/s < U_g < 1.4 m/s			1.4 m/s < U_g < 2.3 m/s		

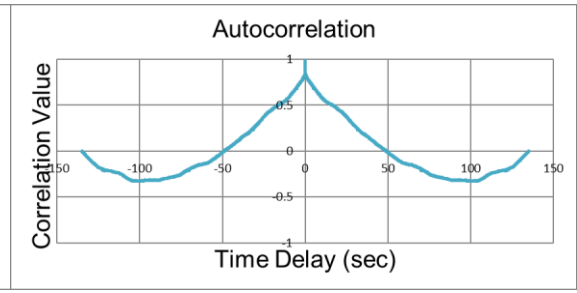


Autocorrelation Data

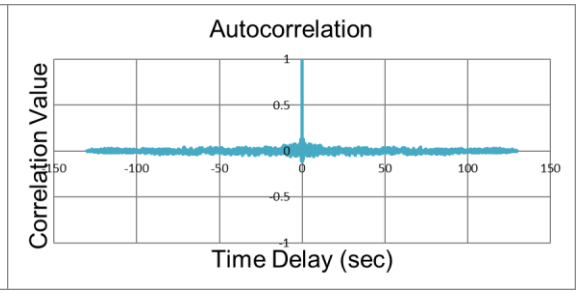
1/2"-equivalent nozzle, 4 inch (0.102 m) Static Bed



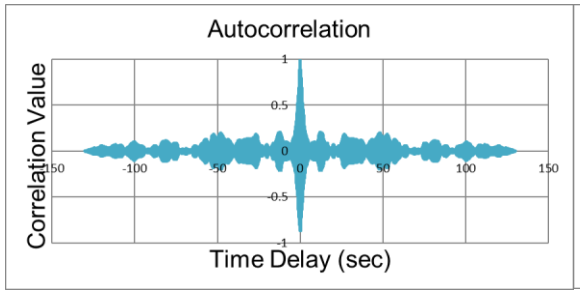
0.43 - 0.70 m/s



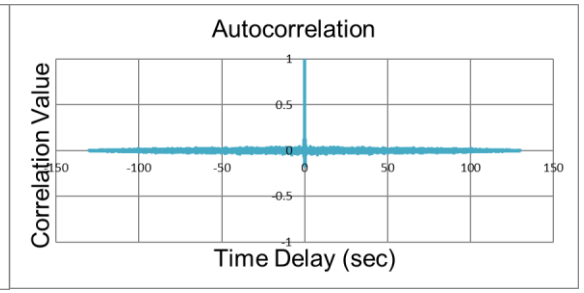
0.76 – 0.87 m/s



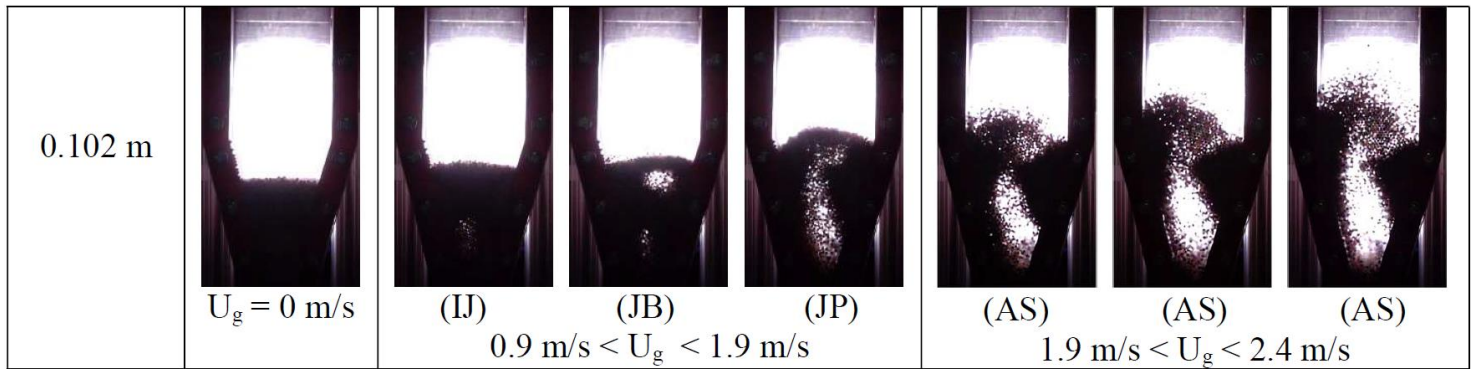
0.98 – 1.08 m/s

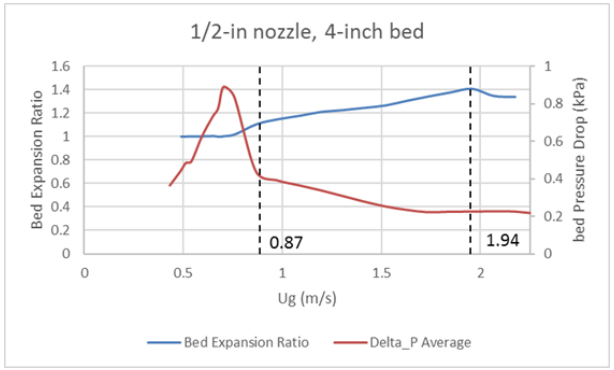


1.19 – 1.84 m/s



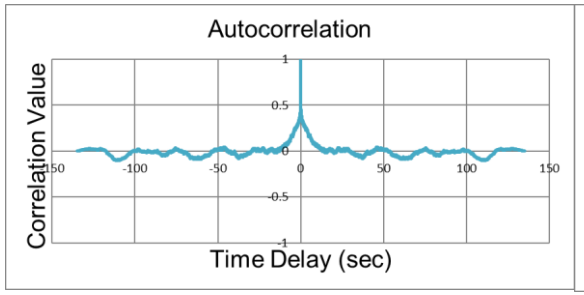
1.95 – 2.4 m/s



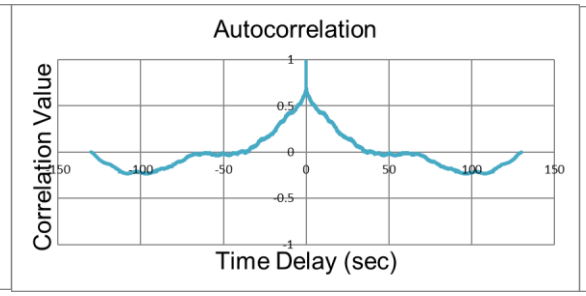


Autocorrelation Data

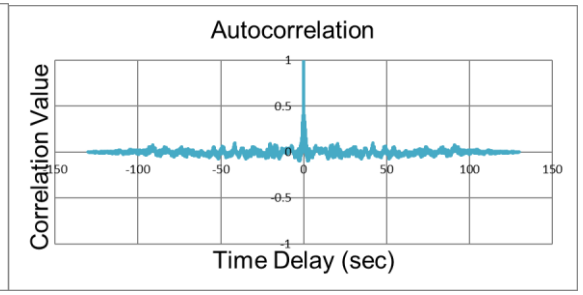
1/2”-equivalent nozzle, 5 inch (0.127 m) Static Bed



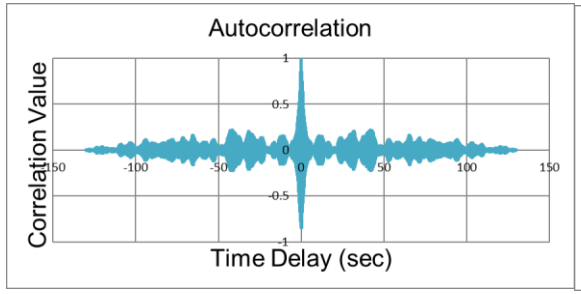
0.54 – 0.87 m/s



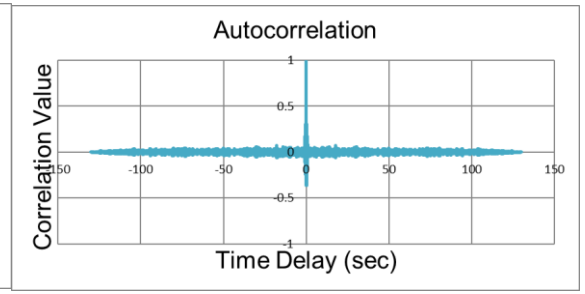
0.974 m/s



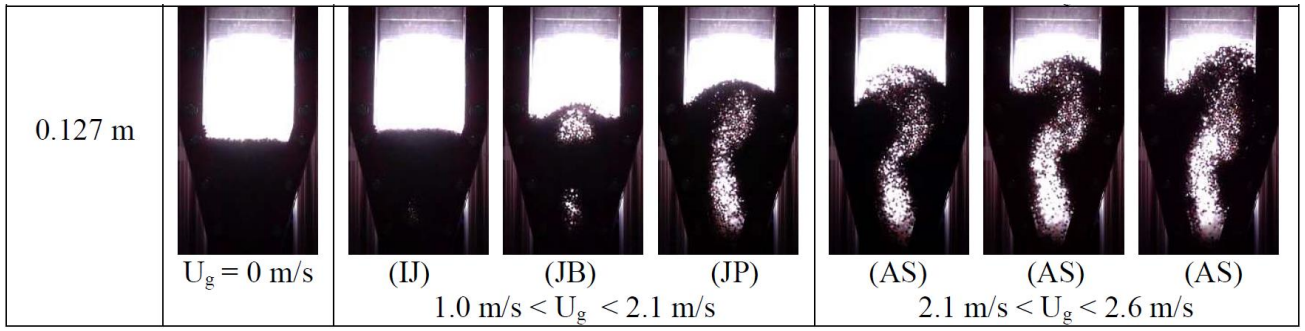
1.08 – 1.20 m/s

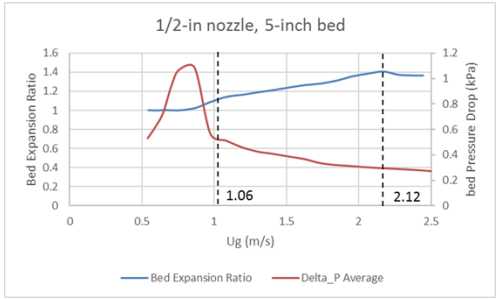


1.30 – 2.17 m/s



2.28 – 2.6 m/s



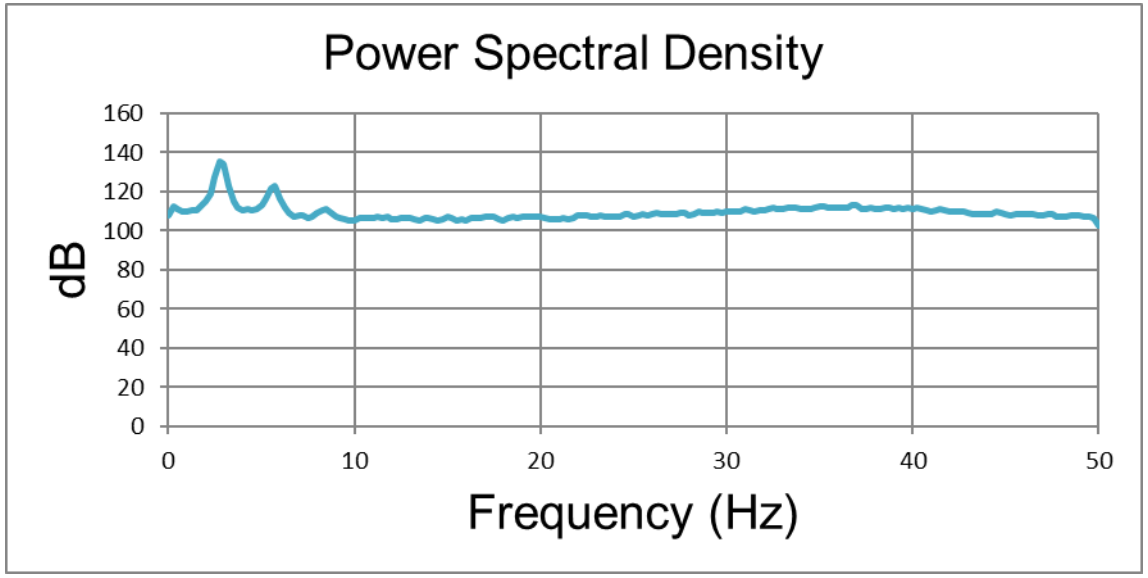


Power Spectral Density (PSD) Data

- **Power Spectral Density:**
  - Related to the autocorrelation via:

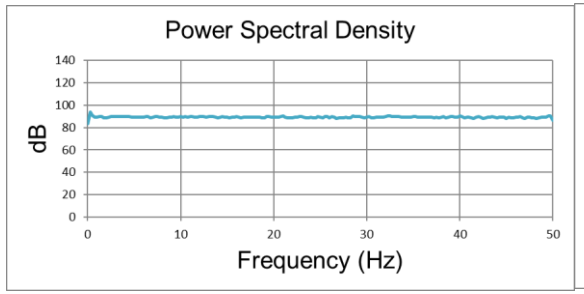
$$S(f) = \sum c_{xx}(\tau) e^{-2\pi i f \tau}$$

  - Provides a measurement of the power associated with a given frequency.
  - Useful for determining dominant frequencies in time series data (i.e. pressure signals).

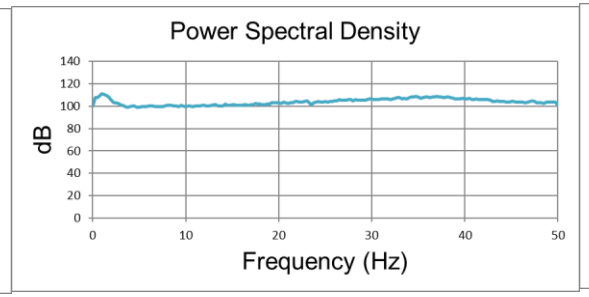


Power Spectral Density (PSD) Data

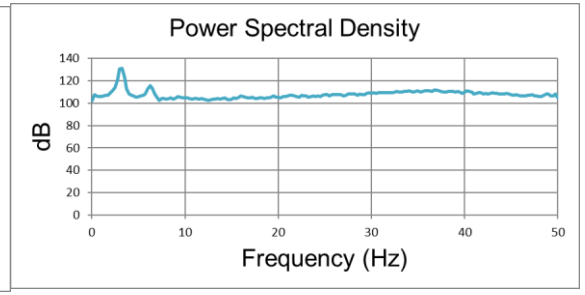
3/8"-equivalent nozzle, 3 inch (0.0762 m) Static Bed



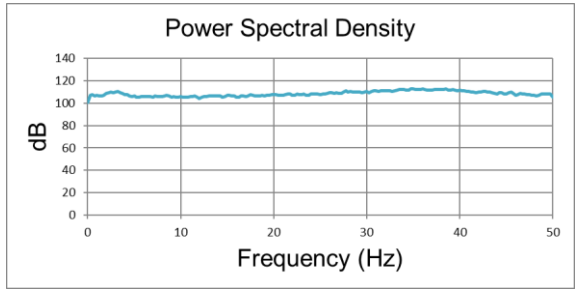
0.44 - 0.57 m/s



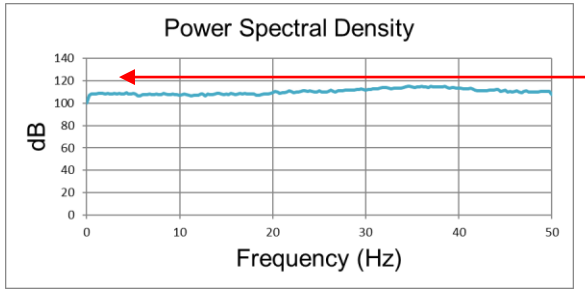
0.60 - 0.82 m/s



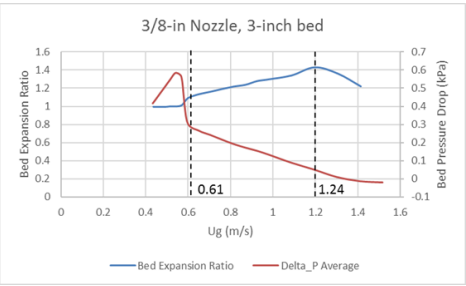
0.87 - 1.20 m/s



1.31 m/s



1.41 - 1.63 m/s

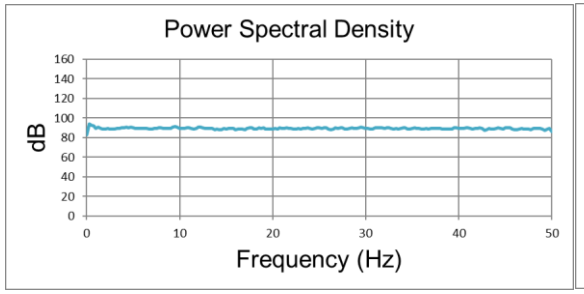


H_0	Static	Jet development			External spouting		
0.0762 m							
	$U_g = 0$ m/s	(IJ)	(IJ)	(JP)	(SS)	(SS)	(DS)
		0.6 m/s < U_g < 1.2 m/s			1.2 m/s < U_g < 1.6 m/s		

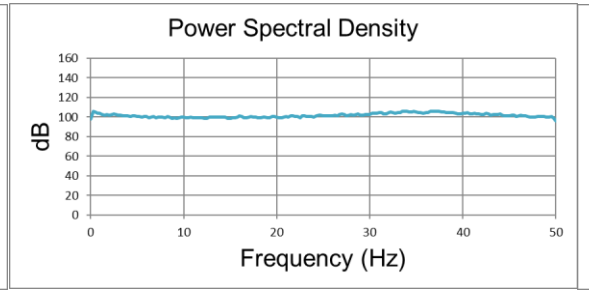
Note that the oeak frequency peak goes away.

Power Spectral Density (PSD) Data

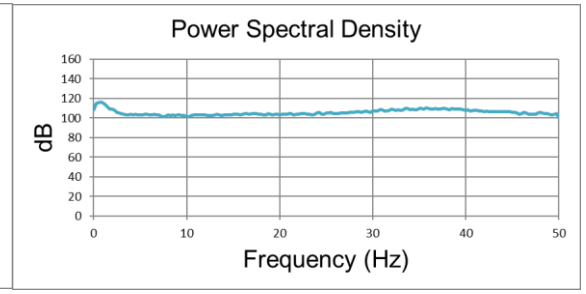
3/8"-equivalent nozzle, 4 inch (0.102 m) Static Bed



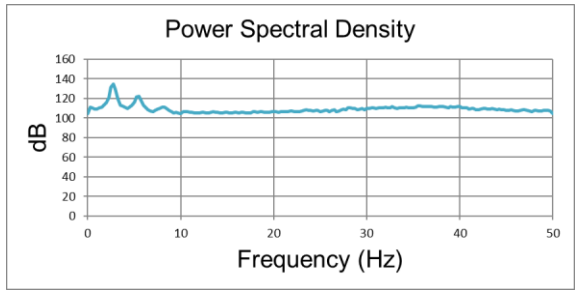
0.49 - 0.60 m/s



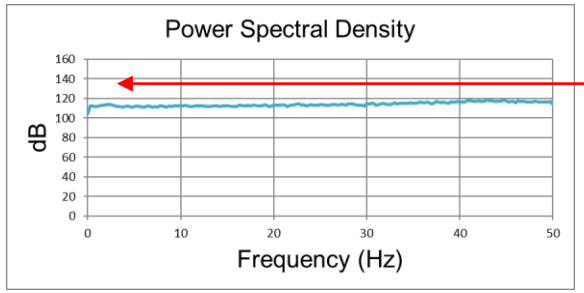
0.63 – 0.76 m/s



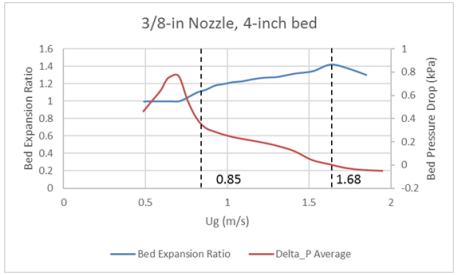
0.82 - 1.03 m/s

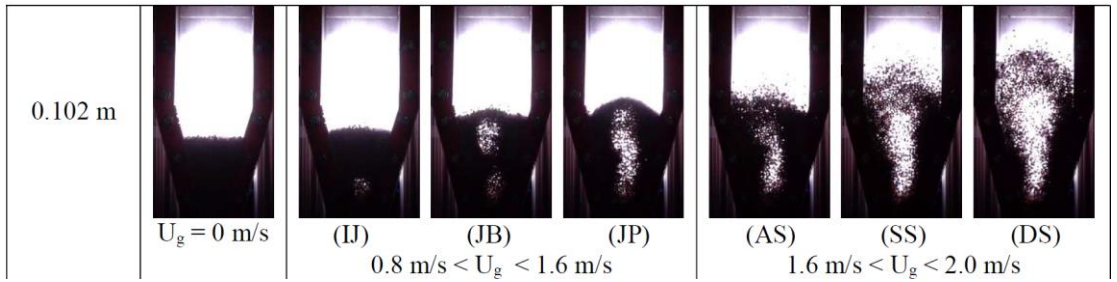


1.08 - 1.52 m/s



1.632 – 1.96 m/s

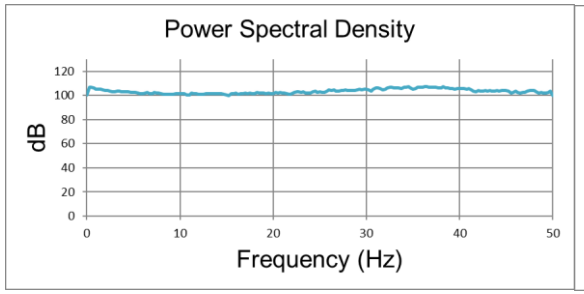




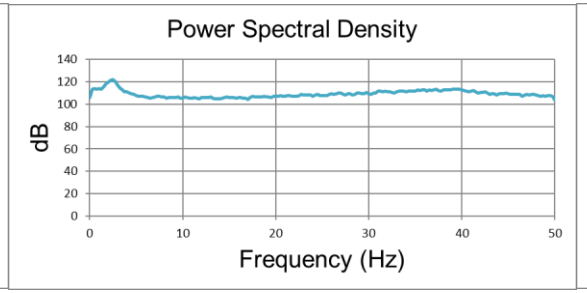
Note that the peak frequency peak goes away.

Power Spectral Density (PSD) Data

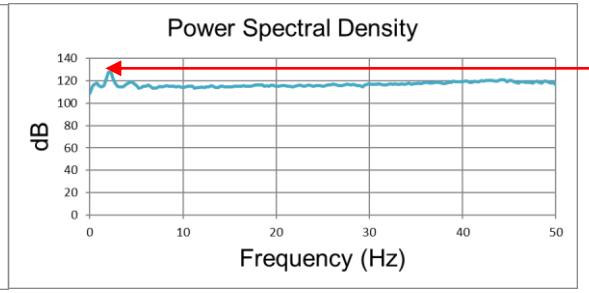
3/8"-equivalent nozzle, 5 inch (0.127 m) Static Bed



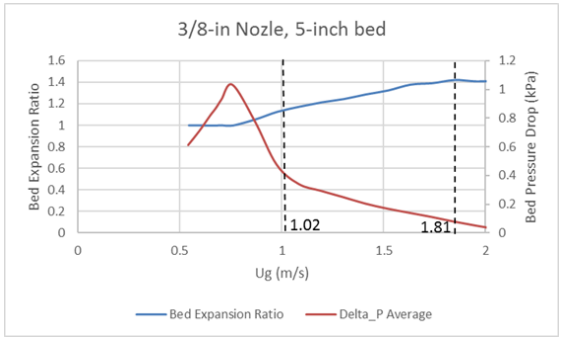
0.54 – 0.87 m/s



0.98 – 1.74 m/s



1.85 – 2.07 m/s

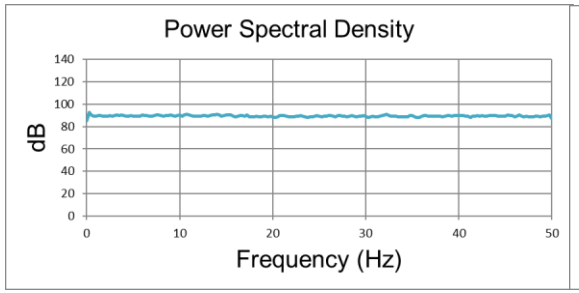


0.127 m							
	$U_g = 0$ m/s	(IJ)	(JB)	(JP)	(AS)	(AS)	(SS)
		$1.0 \text{ m/s} < U_g < 1.9 \text{ m/s}$			$1.9 \text{ m/s} < U_g < 2.1 \text{ m/s}$		

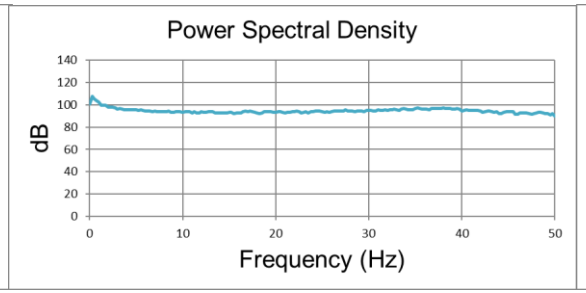
Note: this peak frequency does not go away.

Power Spectral Density (PSD) Data

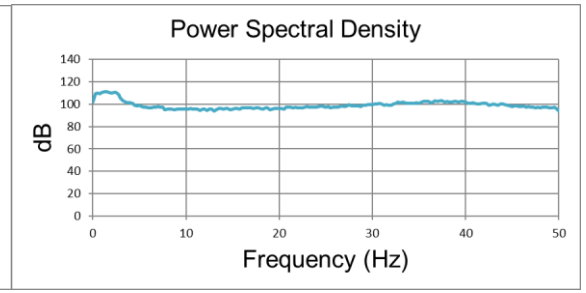
1/2"-equivalent nozzle, 3 inch (0.0762 m) Static Bed



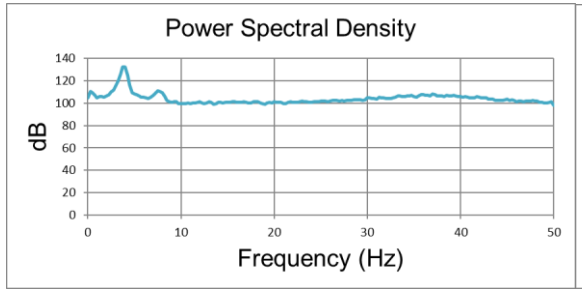
0.27 - 0.51 m/s



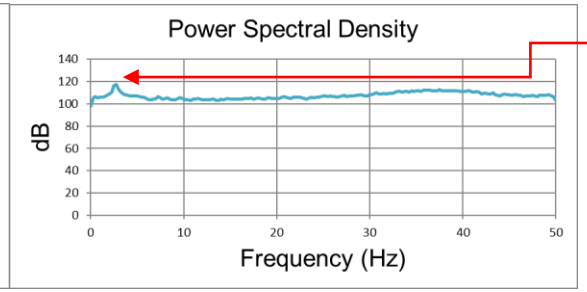
0.541 – 0.76 m/s



0. 87 m/s



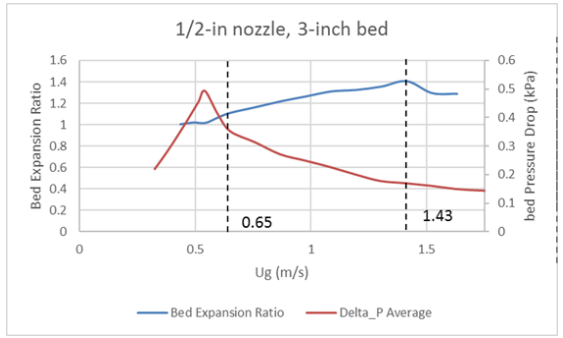
0.98 – 1.3 m/s



1.41 – 2.18 m/s

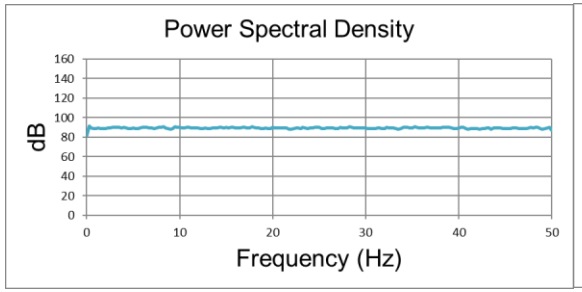
Note: this peak frequency does not go away.

H_0	Static	Jet development			External spouting		
0.0762 m							
	$U_g = 0$ m/s	(IJ)	(IJ)	(JP)	(SS)	(AS)	(AS)
		0.7 m/s < U_g < 1.4 m/s			1.4 m/s < U_g < 2.3 m/s		

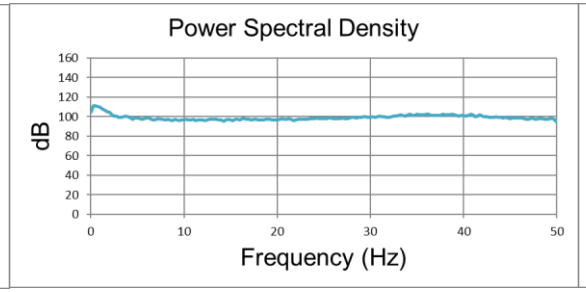


Power Spectral Density (PSD) Data

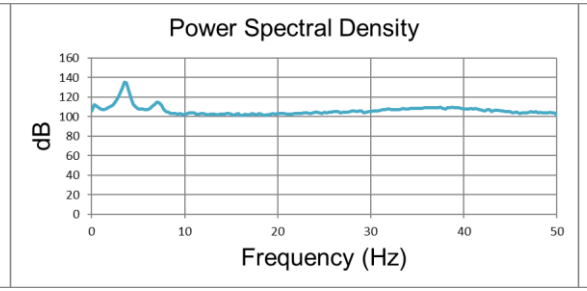
1/2"-equivalent nozzle, 4 inch (0.102 m) Static Bed



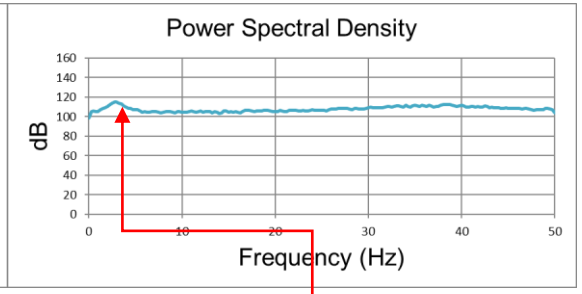
0.43 – 0.70 m/s



0.76 – 1.08 m/s

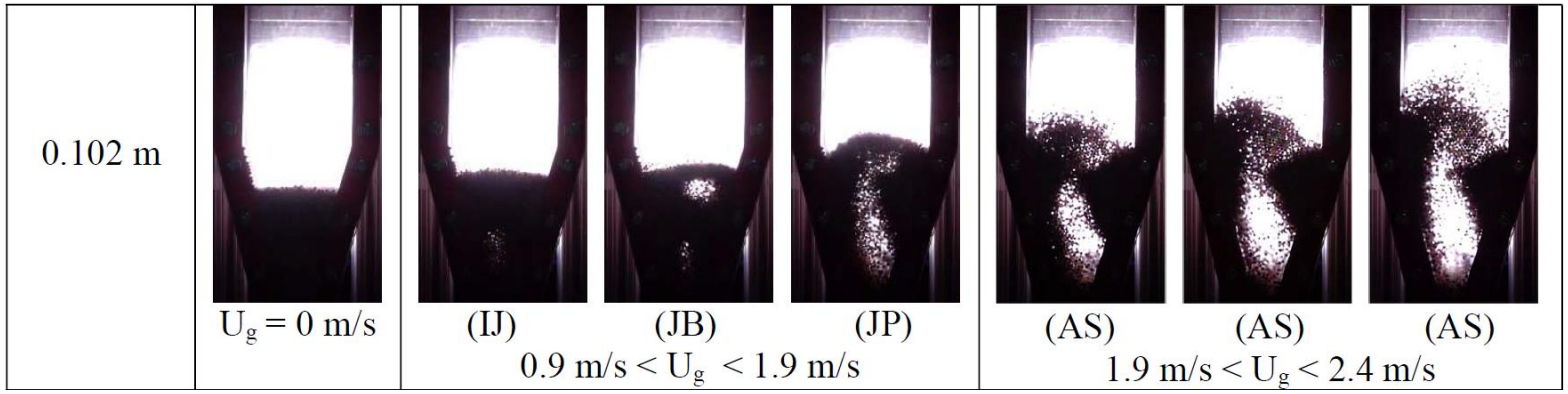


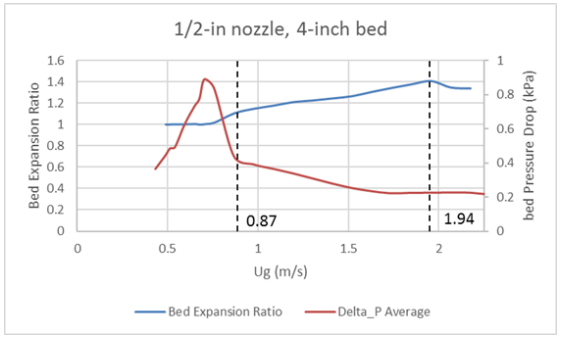
1.19 – 1.95 m/s



2.06 - 2.4 m/s

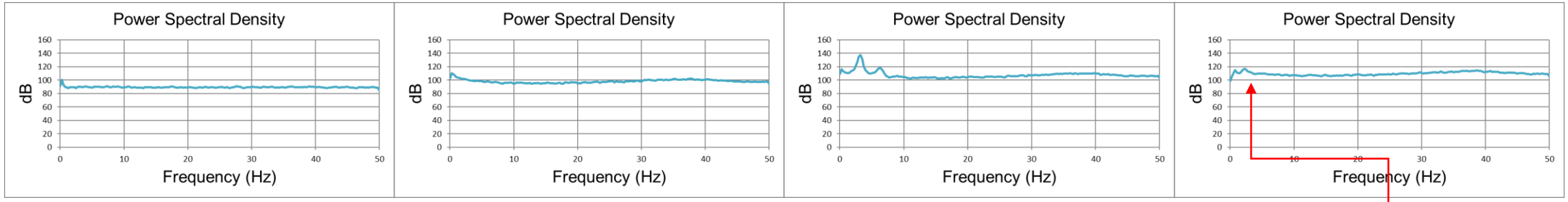
Note: this peak frequency does not go away.





Power Spectral Density (PSD) Data

1/2"-equivalent nozzle, 5 inch (0.127 m) Static Bed



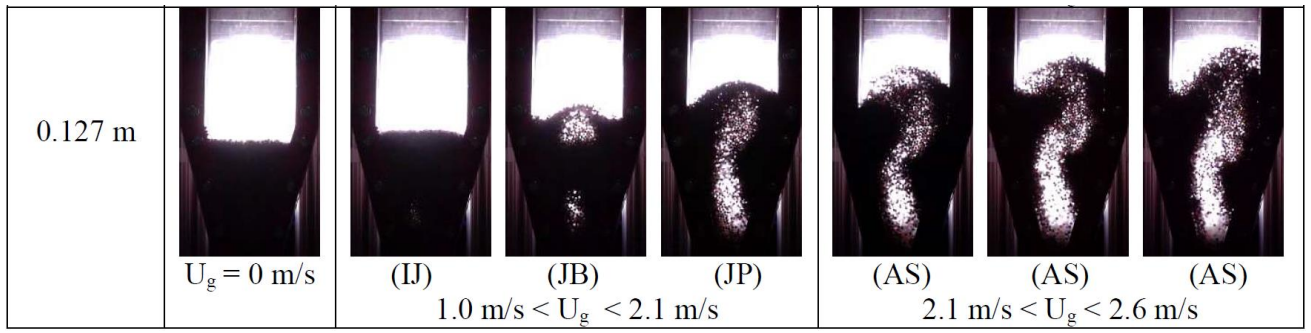
0.54-0.65 m/s

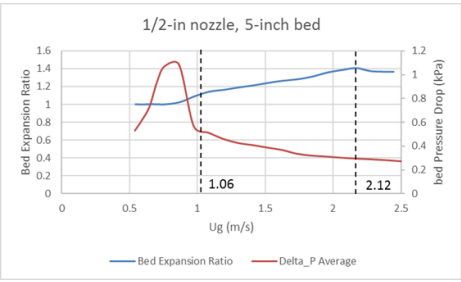
0.76-0.98 m/s

1.08 – 2.27 m/s

2.44 - 2.54 m/s

Note: this peak frequency does not go away.



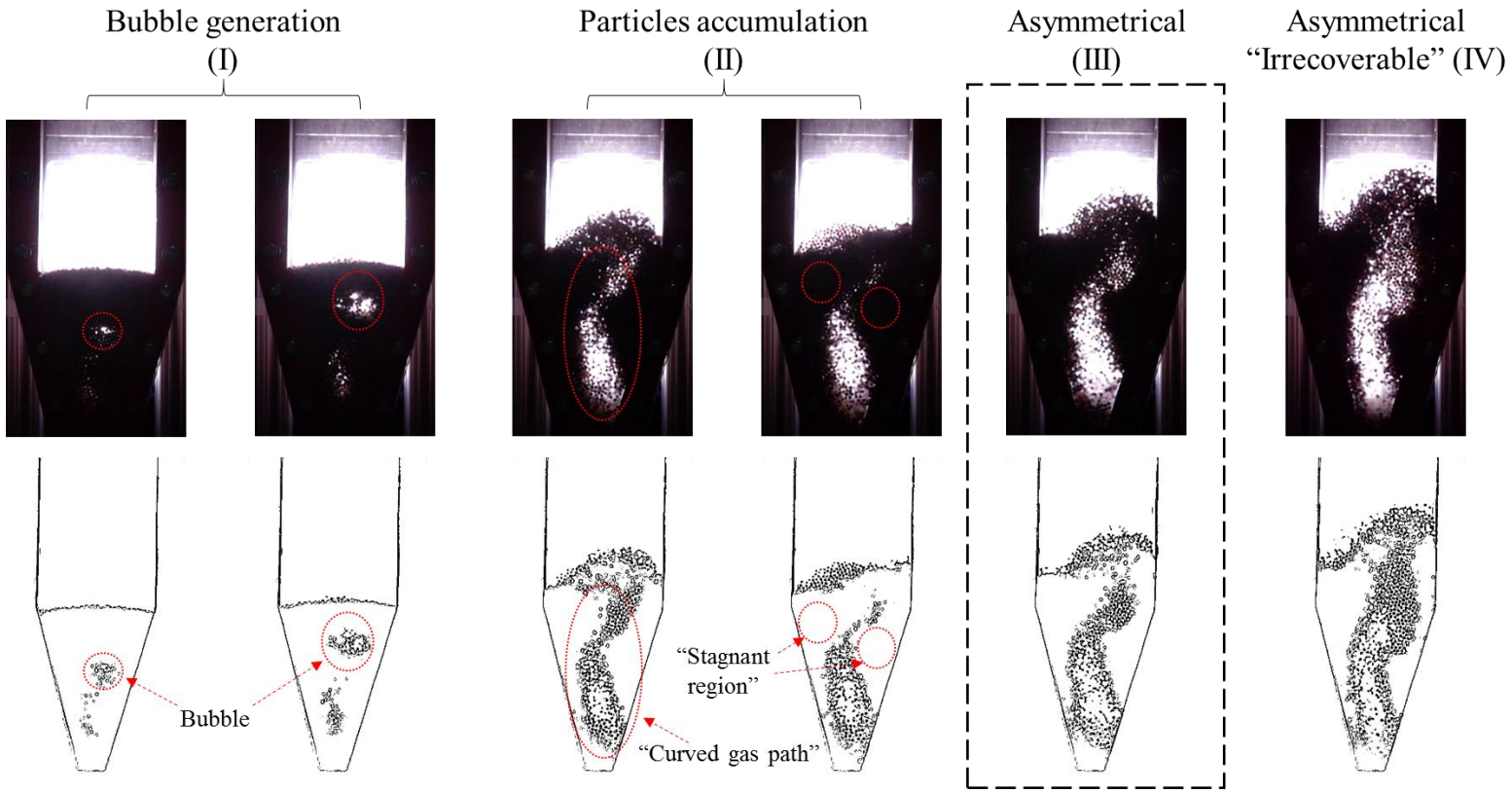


Making Sense of the Data

Questions to answer:

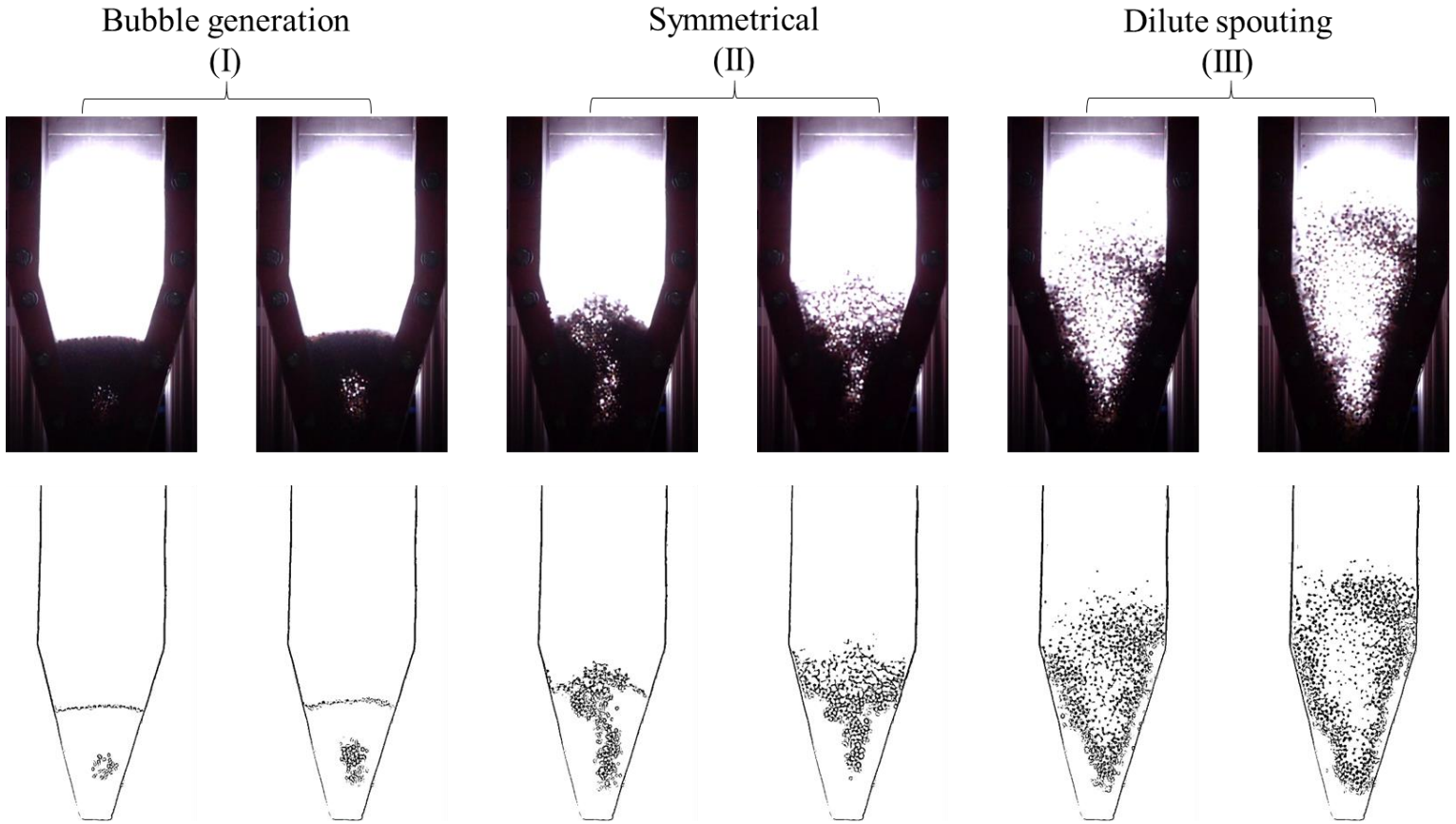
- Why does the highest bed height/smallest nozzle case bypass the jet-bubbling regime?
- What is the cause of the ~3hz dominant frequency in the asymmetric spouting cases?

A Closer Look at Symmetric Spouting



- Asymmetries begin to appear in the internal spouting regime and grow progressively worse.
- The jet "curves" around zones of stagnant particles.
- Particles tend to be ejected into the freeboard in a non axially-symmetric manner.
- This tends to constantly replenish and solids entrained out of the stagnant zones, thus attenuating the asymmetries.
- The authors believe that the interactions between the gas jet and these stagnant zones may lead to the presence of the ~3 Hz dominant frequency present during asymmetric spouting.

A Closer Look at Asymmetric Spouting



- In comparison to asymmetric spouting, symmetric spouting does not exhibit the formation of stagnant zones of solids.
- At higher gas velocities, the symmetric spout tends to transition to dilute spouting.
- It is assumed that the lack of interactions between the gas jet and stagnant solids zones, as well as the more dispersed nature of the the spouting at higher gas velocities, is what allows the ~3 Hz pressure fluctuations to die out during symmetric external spouting.

Conclusions:

- **In this on-going work, the spouting behavior of 3.2mm Nylon beads was examined for a range of nozzle sizes and static bed heights.**
- **It was observed that:**
  - The smaller nozzle size generally led to more stable (i.e. symmetric) spouting.
  - The larger nozzle size lead to asymmetric spouting conditions, and the formation of stagnant zones of solids within the annulus region.
  - Asymmetric spouting is preceded by a more vigorous jet-bubbling phase.
  - The presence of a low frequency peak in the spectral density of the pressure data suggests an interaction between the gas jet and the stagnant solids zones under conditions of asymmetric spouting.

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DISCLAIMER

The authors declare no competing financial interest.

Questions?

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