



Driving Innovation ♦ Delivering Results



Microwave Doppler Sensing of Sliding or Intermittent Particle Flows

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August 10, 2016



U.S. DEPARTMENT OF
ENERGY

National Energy
Technology Laboratory

Overview



- **Introduction – Chemical Looping**
- **NETL's Chemical Looping Reactor**
- **Microwave Doppler**
- **Measurement of L-valve flow**
- **Conclusions**

Why Chemical Looping?



- **Options for *coal power* carbon dioxide capture/control:**
 - Solvent scrubbing
 - Advanced sorbents
 - Membranes
 - Oxy-fuel combustion: requires oxygen
- **Chemical Looping:**
 - No oxygen plant needed
 - Similar to familiar fluid bed technology
- **How can you “get there” quick (i.e., deploy, demonstrate)?**
 - Industrial applications- smaller size, easier NG fuel.
 - Possibly supply CO₂ to chemical/EOR needs?

For an update on the status of these technologies:

2015 NETL CO₂ CAPTURE TECHNOLOGY MEETING

Jun 23 – 26, 2015

Web-link listed below.



Coal



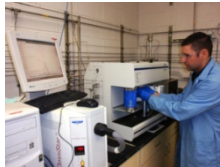
Natural gas

<http://www.netl.doe.gov/events/conference-proceedings/2015/2015-co2-capture-technology-meeting>

Integrated Experimental & Modeling Effort



TGA and
Mass-Spec



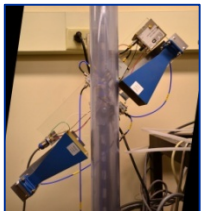
Lab-scale
Fixed Bed
Reactor



Integrated
Cold Flow
Unit



Chemical Looping Reactor



Microwave
Sensor

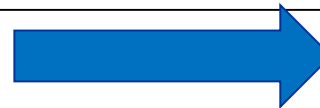


Single Fluidized
Bed Reactor

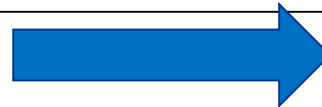
Carrier Development/Evaluation
reaction model development via.
parameter estimation



Bed Reaction Rate
Reaction model validation
Small scale validation of hydro,
reaction and interactions

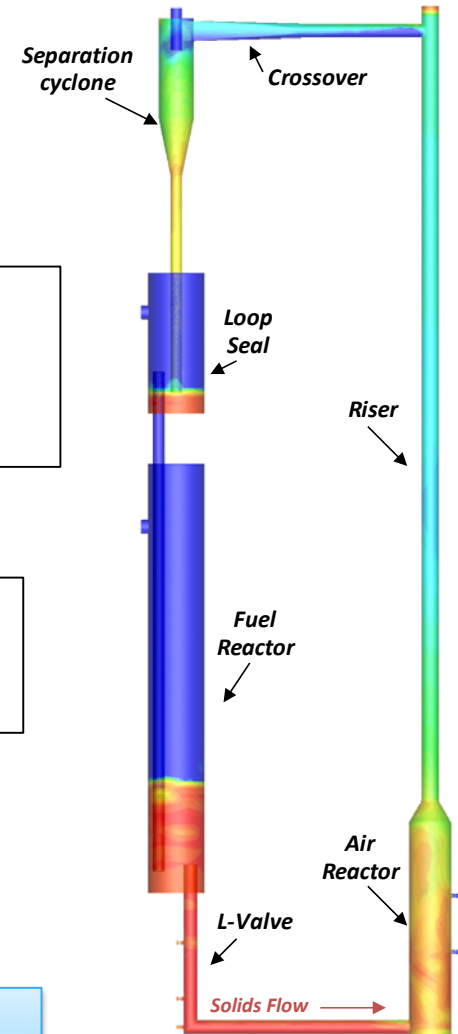


Circulating Hydrodynamics V&V
Solids Handling and Process
Development



**Specialized Sensors and
Instrumentation**

Sensor challenge: operation at 1000°C,
~63 g/s (500 pph) of material, pressurized

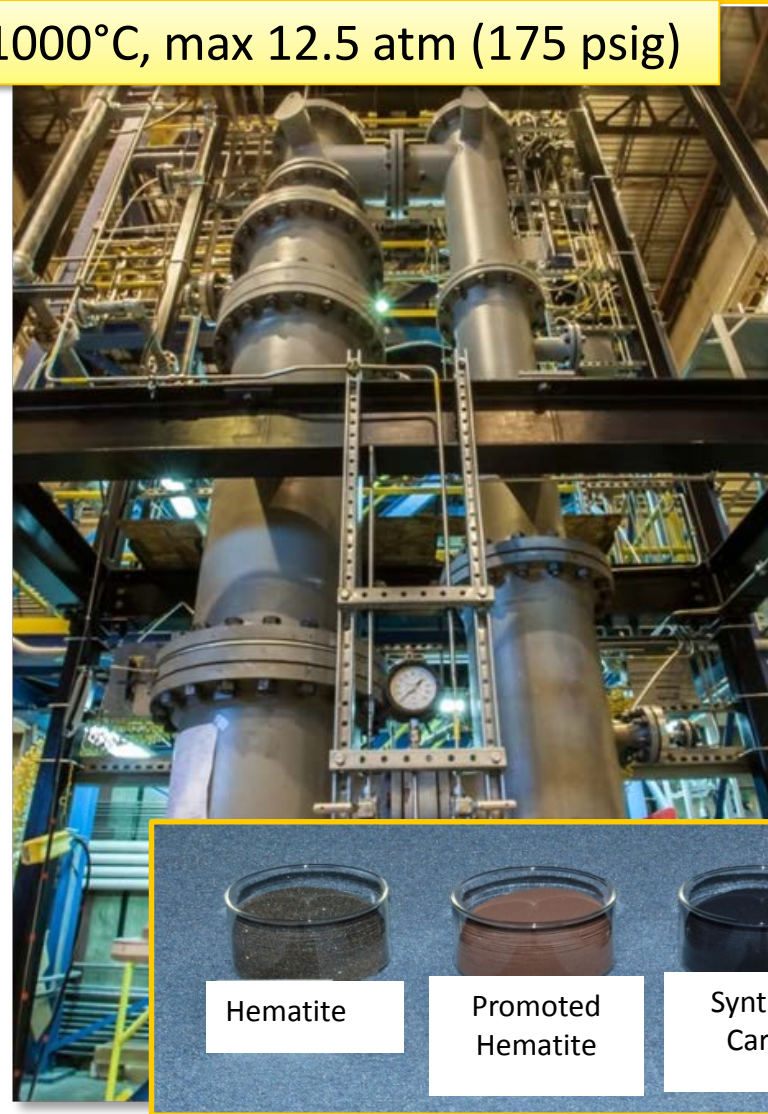
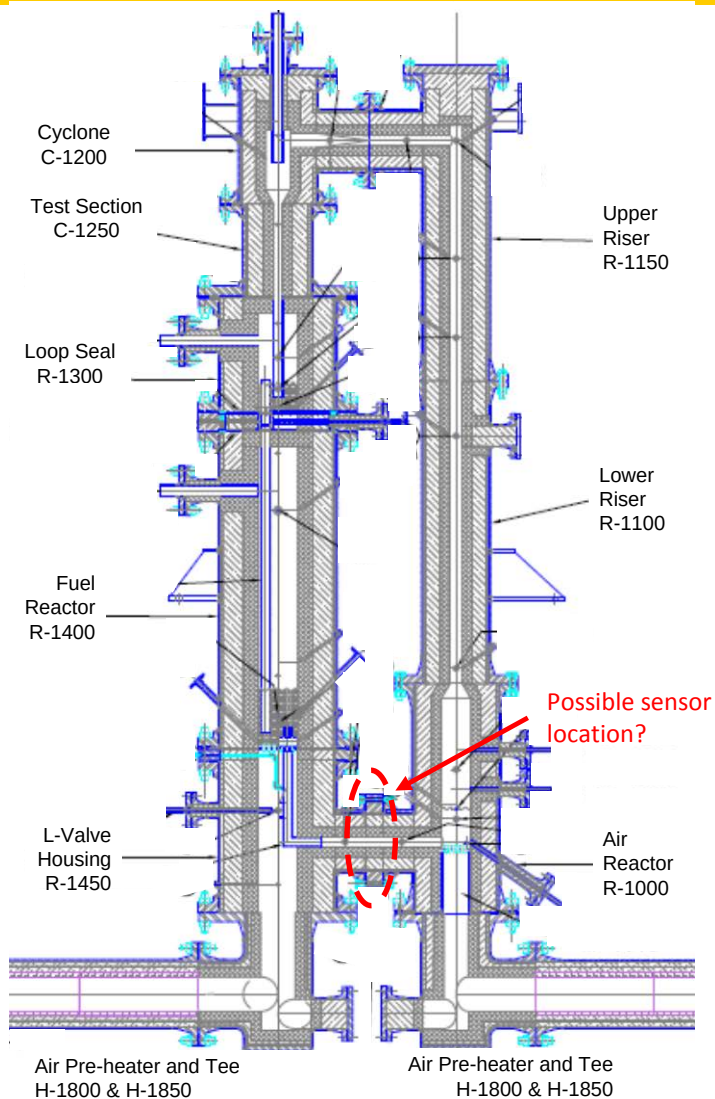


3D multi-phase CFD modeling

NETL Chemical Looping Reactor



1000°C, max 12.5 atm (175 psig)



Hematite



Promoted Hematite



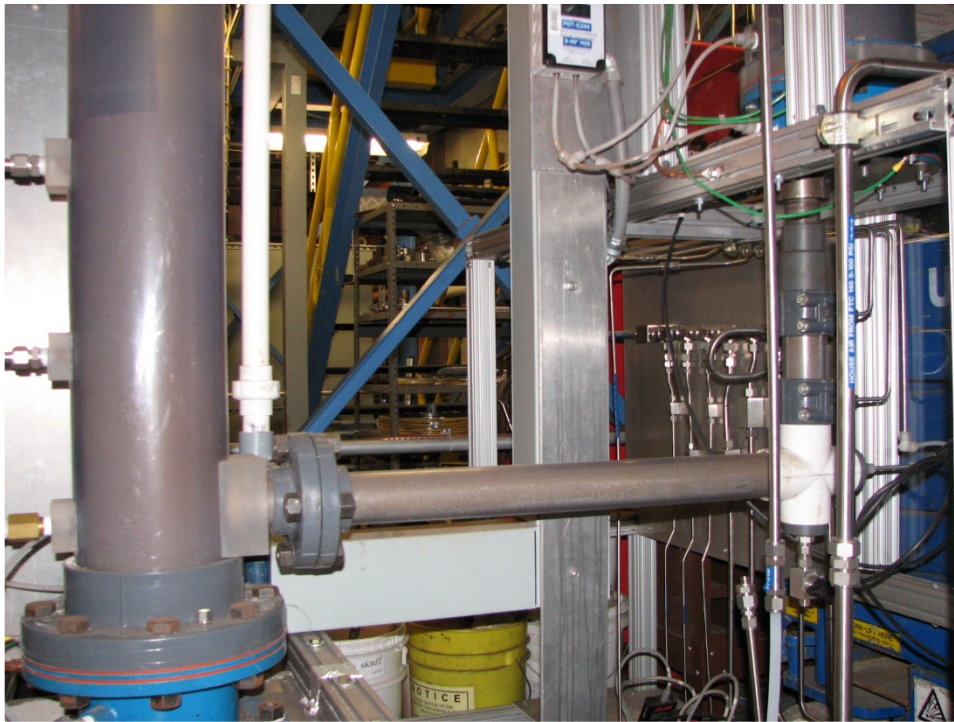
Synthetic Carrier



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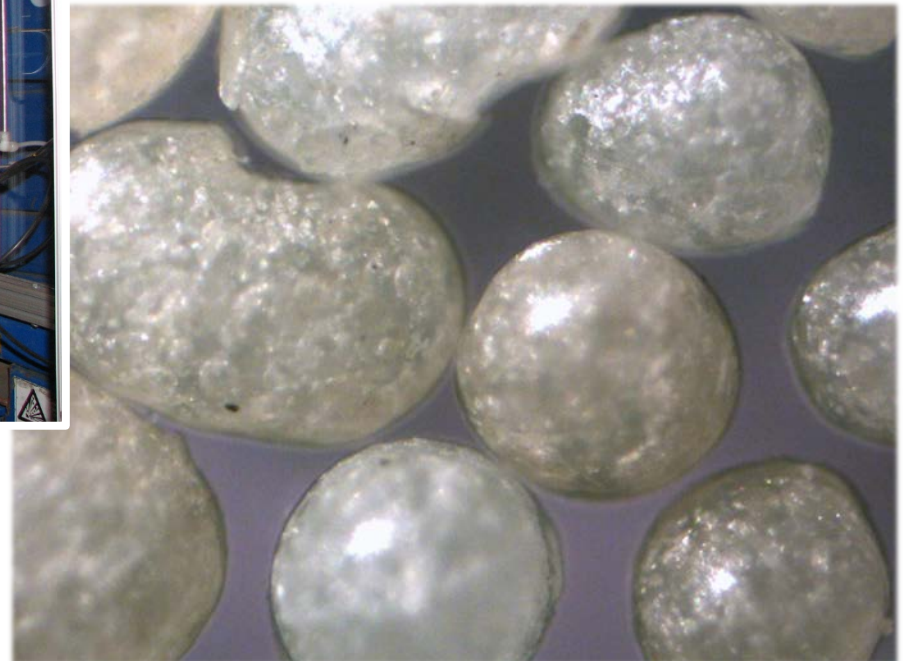
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Cold Flow CLR

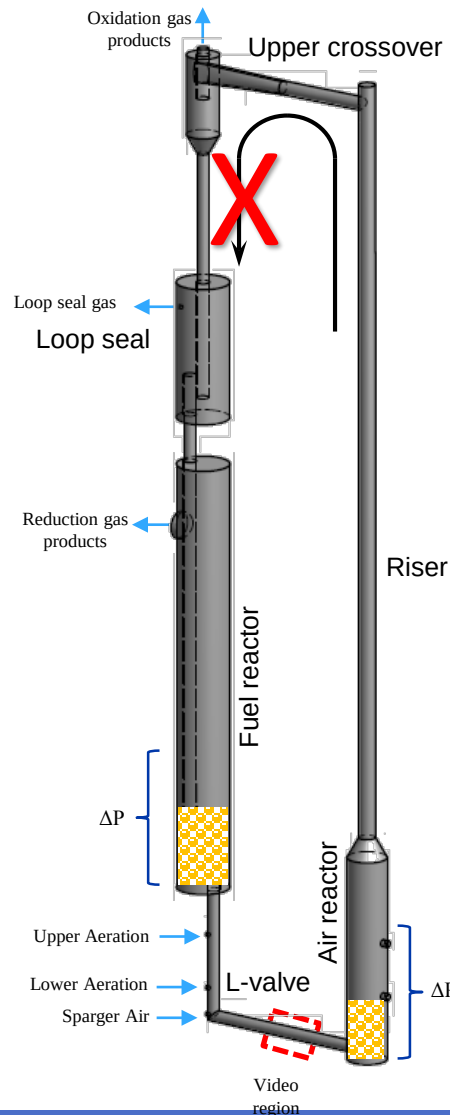


Same inside geometry as CLR
L-valve ID = 50 mm

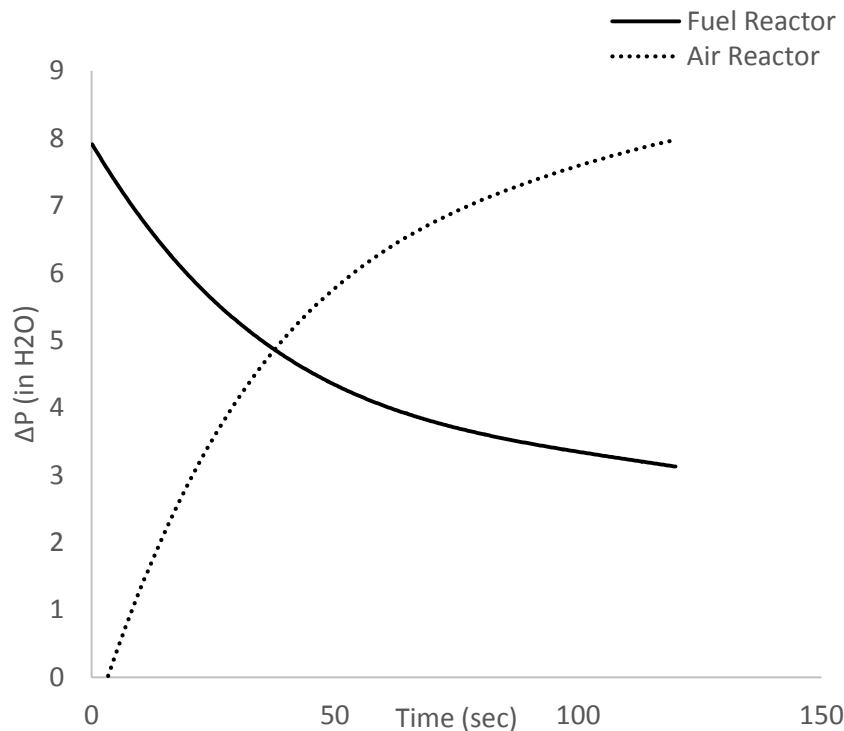
800 micrometer HDPE
Geldart B particles
Sauter Mean Particle Size: $871 \mu\text{m}$
Particle density 0.86 g/cm^3
Minimum fluidization velocity: 17.4 cm/s
Refractive index ~ 1.5 @ 10 GHz



Flow from Pressure Drop across Reactors



Special case with no circulation through riser



L-valve ID = 50 mm

Sparger air 40 SLPM

Lower aeration 10 SLPM, upper aeration 5 SLPM

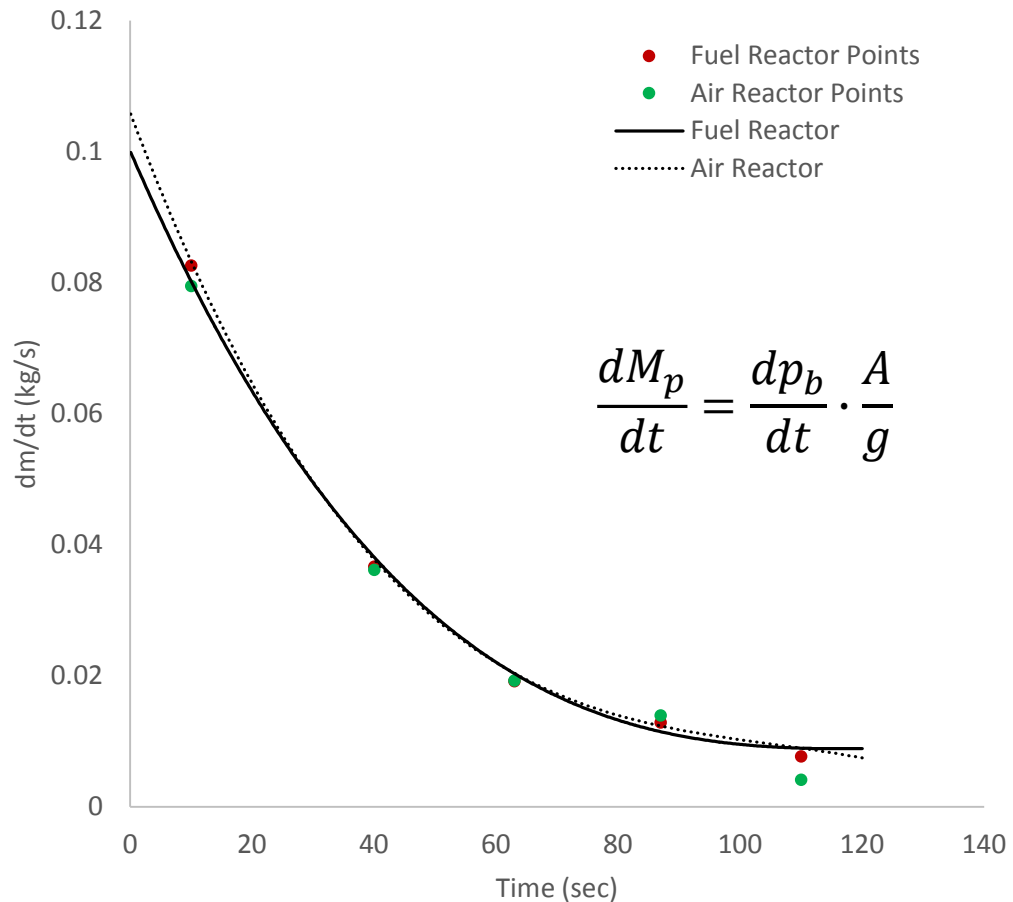
Flow derived from pressure drops



- Fully fluidized bed, pressure drop balances weight of bed (see Fan and Zhu*)
- Assume voidage independent of height, neglect weight of gas

$$\Delta p_b = \frac{M_p g}{A}$$

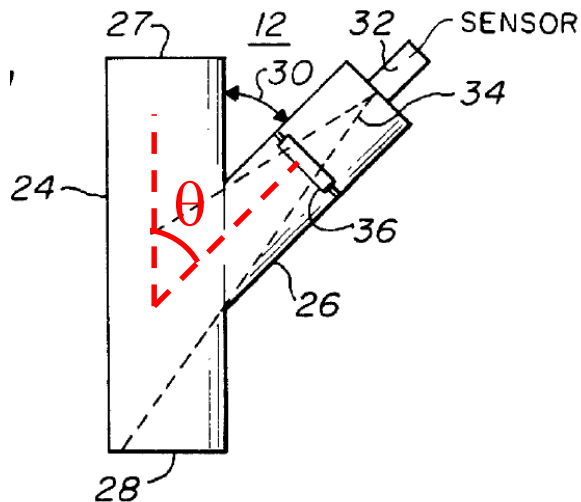
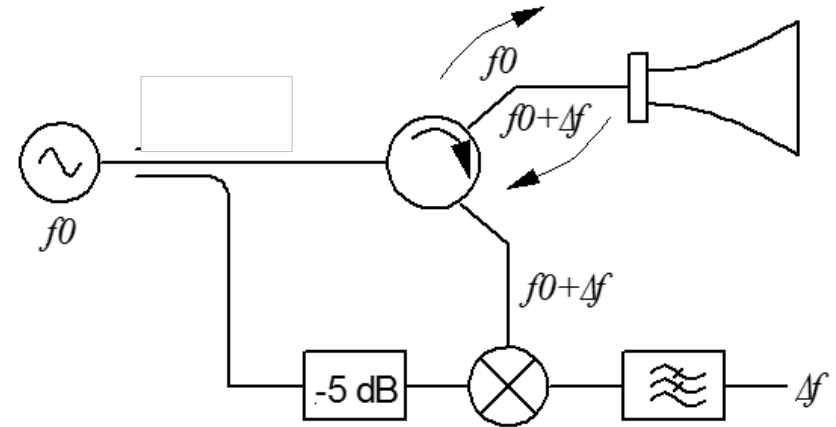
- Flow declines during the test as FR empties
- Average points related to video segments
- Flow appears smooth in pressure data



*Fan, L.S., and Zhu, C. *Principles of Gas-Solid Flows*, Cambridge University Press, Cambridge, 1998 (pp. 378-379)

Microwave Doppler

- Flow velocity determined from Doppler effect (frequency shift)
- Reflection magnitude related to density



$$\Delta f = 2 f \frac{v}{c} \cos \theta$$

$$P_{\text{reflected}} = N \sigma_{\text{total scattering}} P(x) dx$$

number density

scattering cross-section

particle velocity

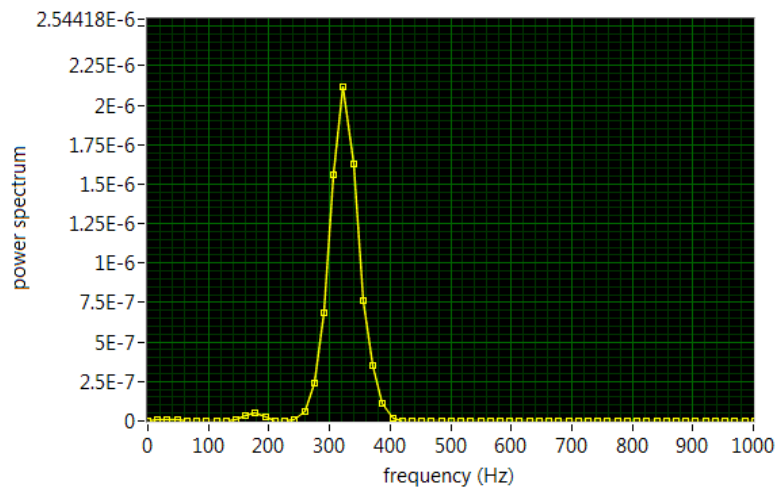
47 Hz per
m/s @ 45°,
10 GHz

Single particle vs. flow of many particles



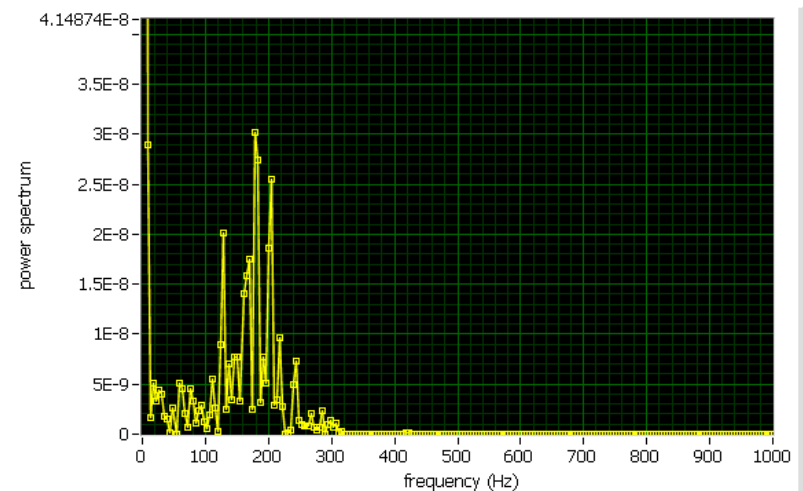
- Compute Fourier power spectrum of demodulated signal
- Get frequency shift of reflected signal

Single Particle



steel ball 0.157" diameter
falling 1.8 m, horn angle 42
degrees; 10 GHz

Many Particles



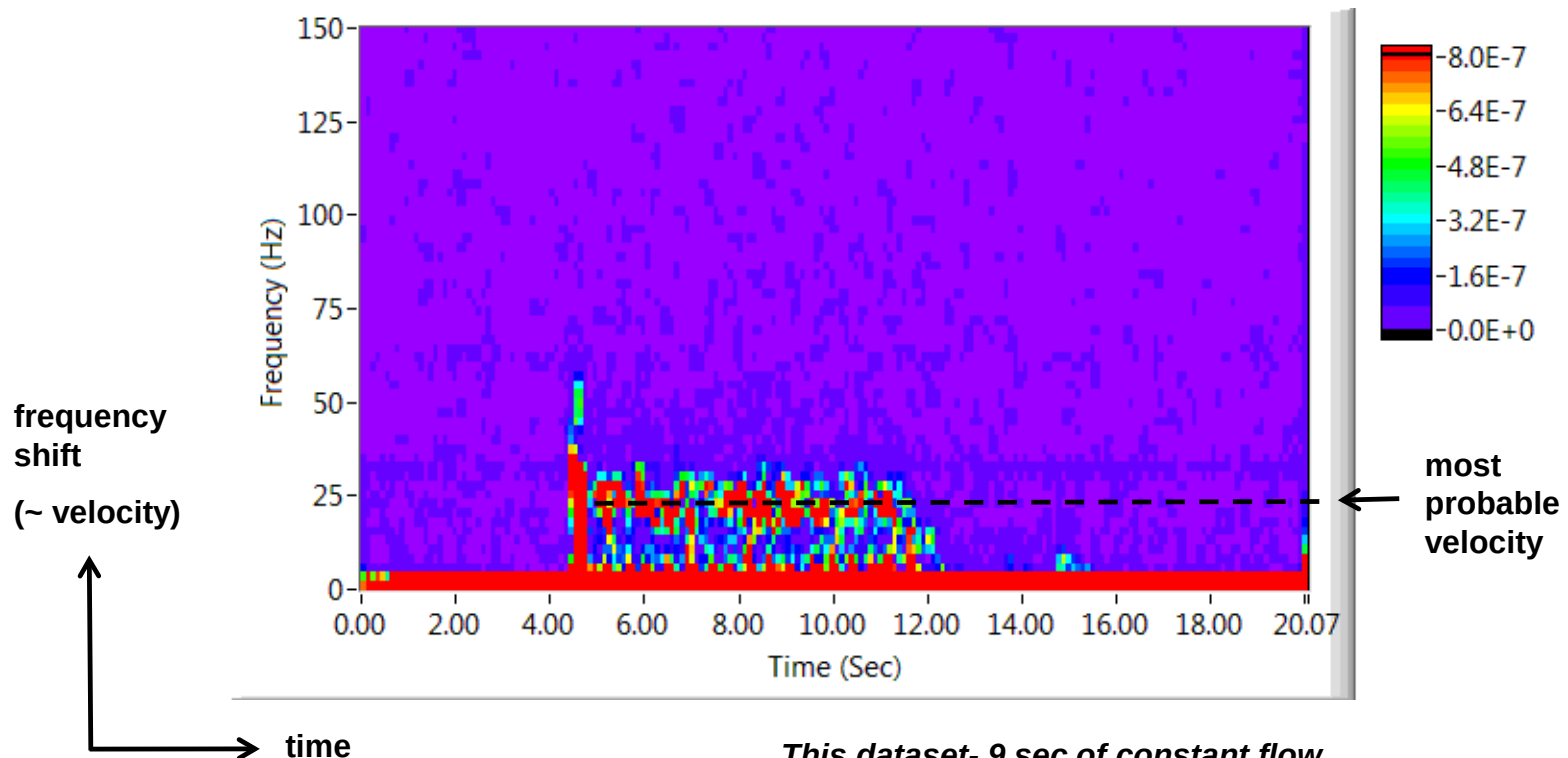
ilmenite falling 2.1 m, horn angle 52
degrees; 10 GHz

Many particles produce a
frequency shift *distribution*

Visualizing velocity for time-varying flow



1. Perform a short-time Fourier transform
2. Make a time-frequency plot



*This dataset- 9 sec of constant flow
from table feeder*

Video from L-valve



- Data in the following slide is taken from dataset (condition4-15-52-59-f.avi)



4-15-52-59-f.-mo
vie

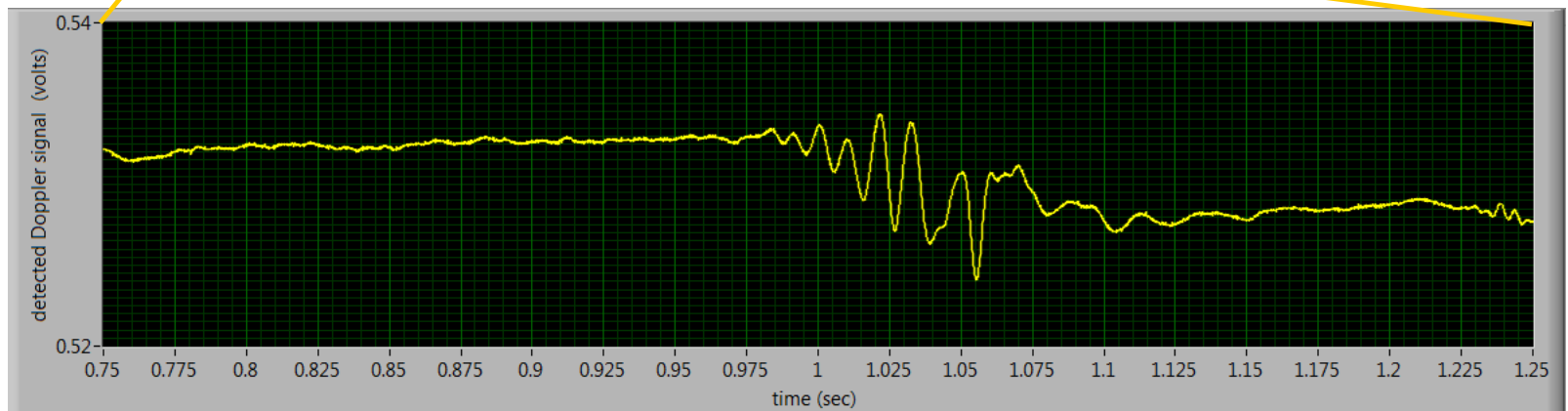
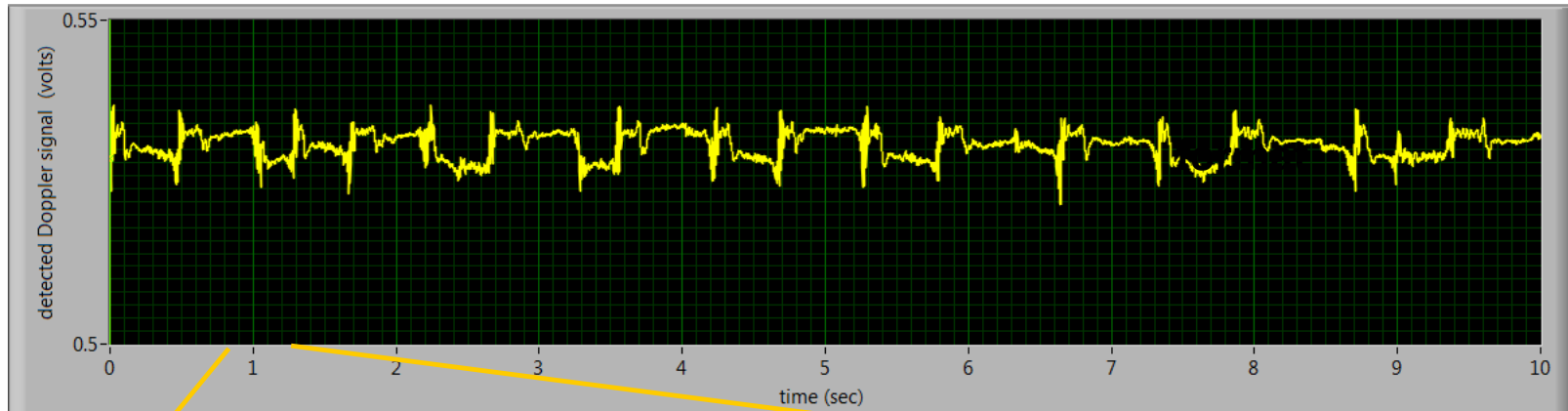
Typical video from L valve



- V



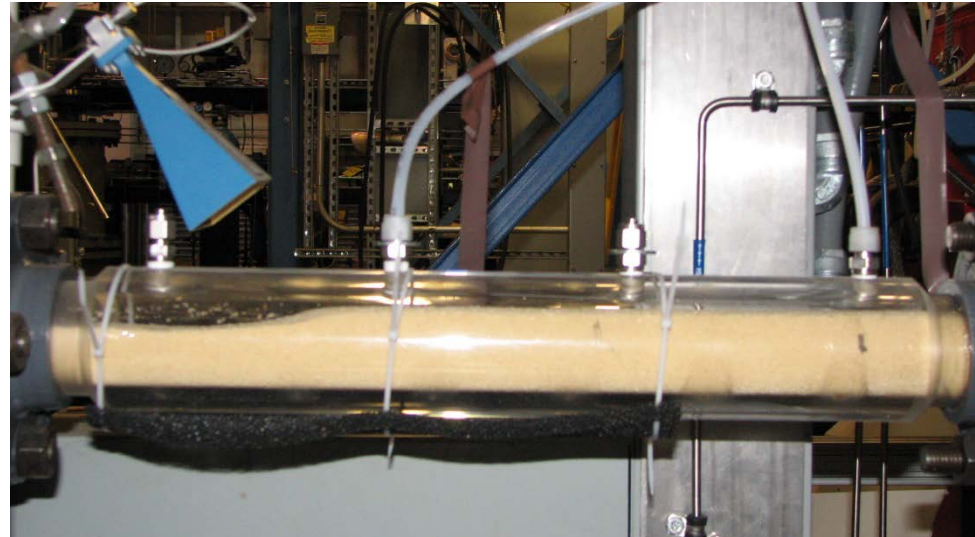
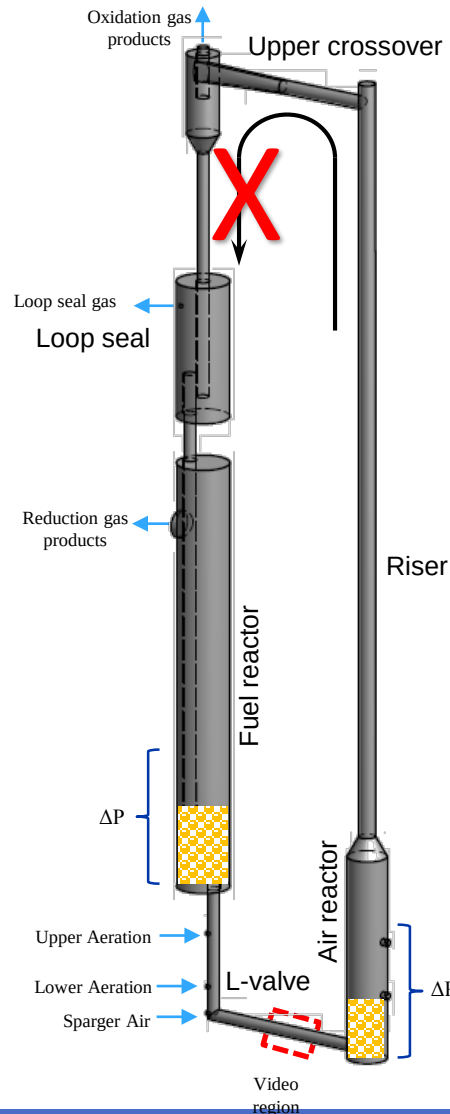
Detected Doppler signal



Constant when particle mass
is stationary

Oscillatory when particle mass
is moving (Doppler shift)

Time-sync'd microwave Doppler and video

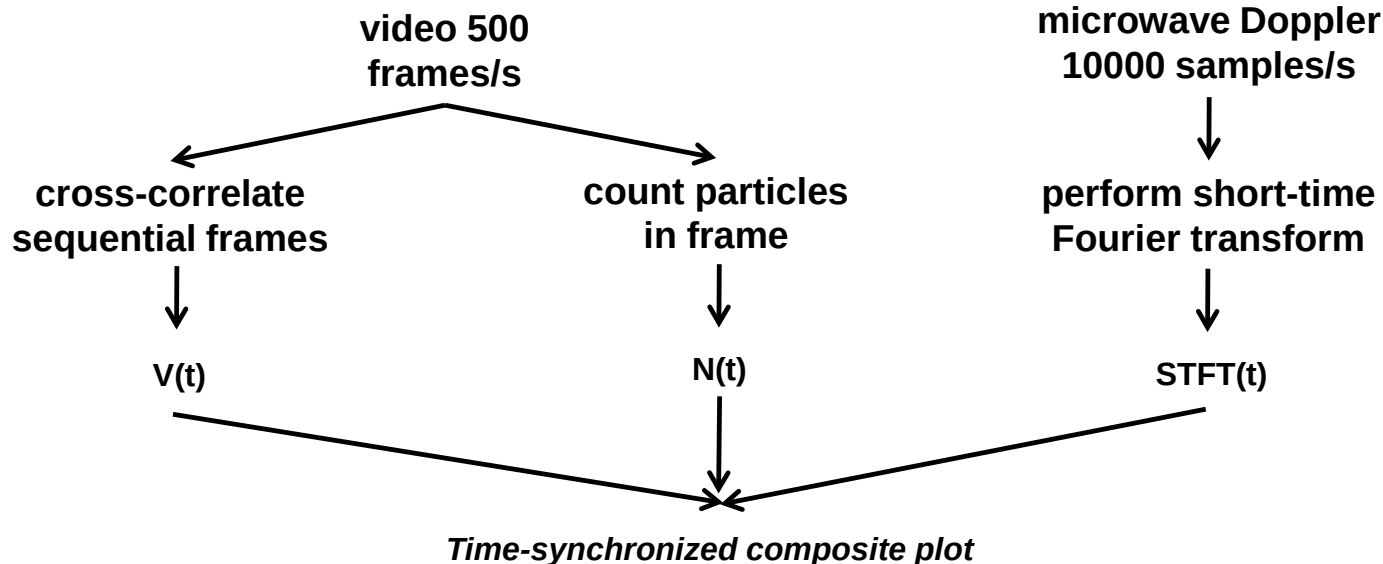
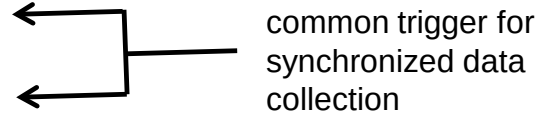


- Several datasets collected during same test as flow through L-valve decreased
- Composite plots made of detected Doppler signal, particle number, velocity from video, and Doppler short time Fourier transform

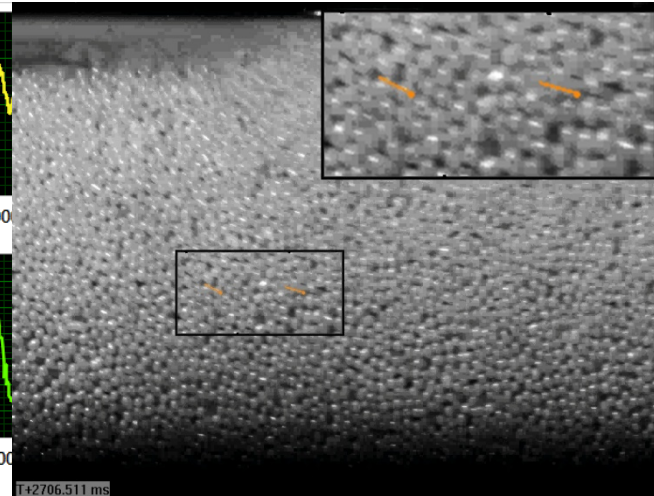
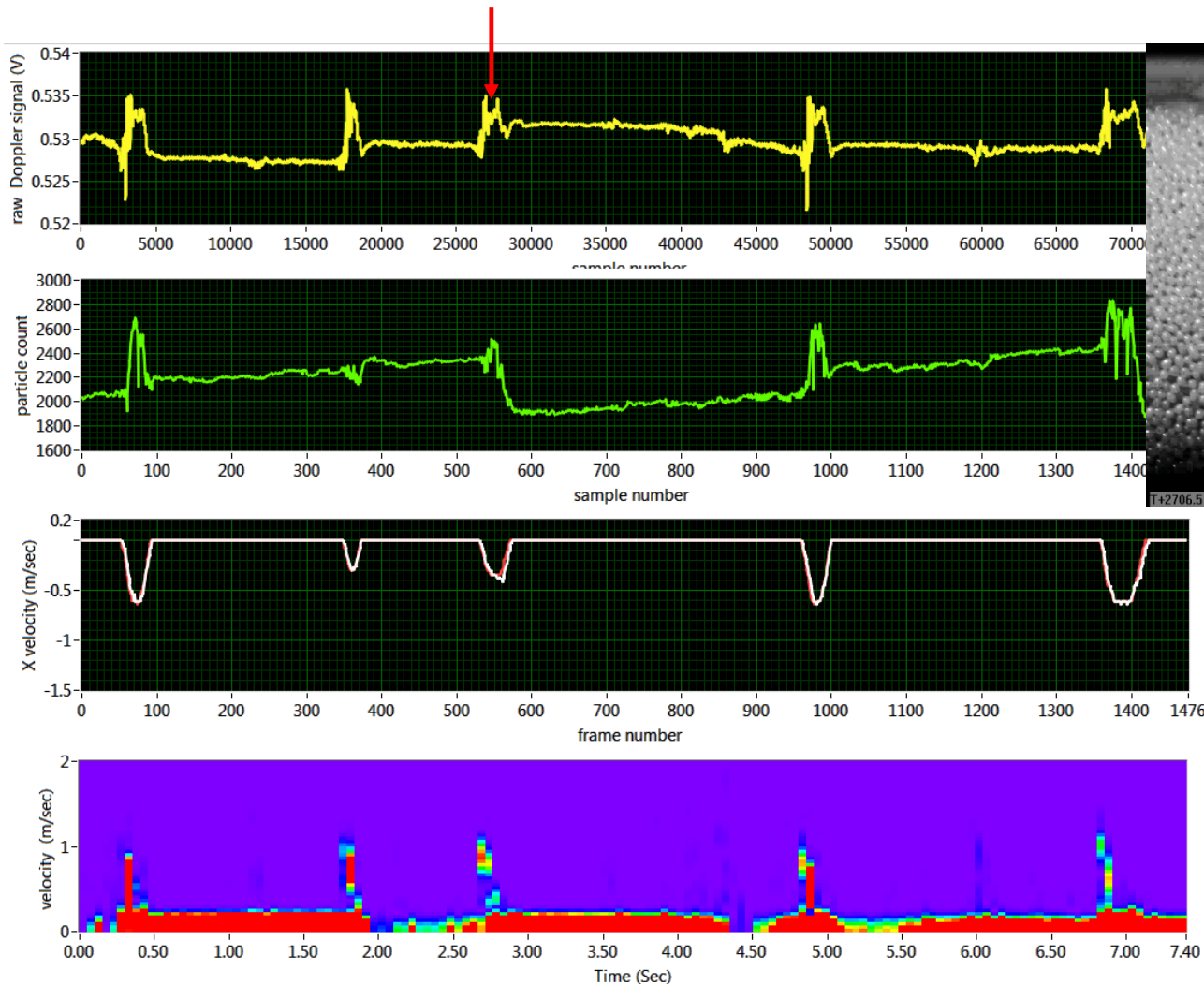
Microwave Doppler for intermittent flow



1. Experiments performed in cold-flow system with transparent L valve
2. Create time-varying flow in L valve
3. Collect high-speed video (500 frames/sec)
4. Collect microwave Doppler data (24 GHz)
5. Compare



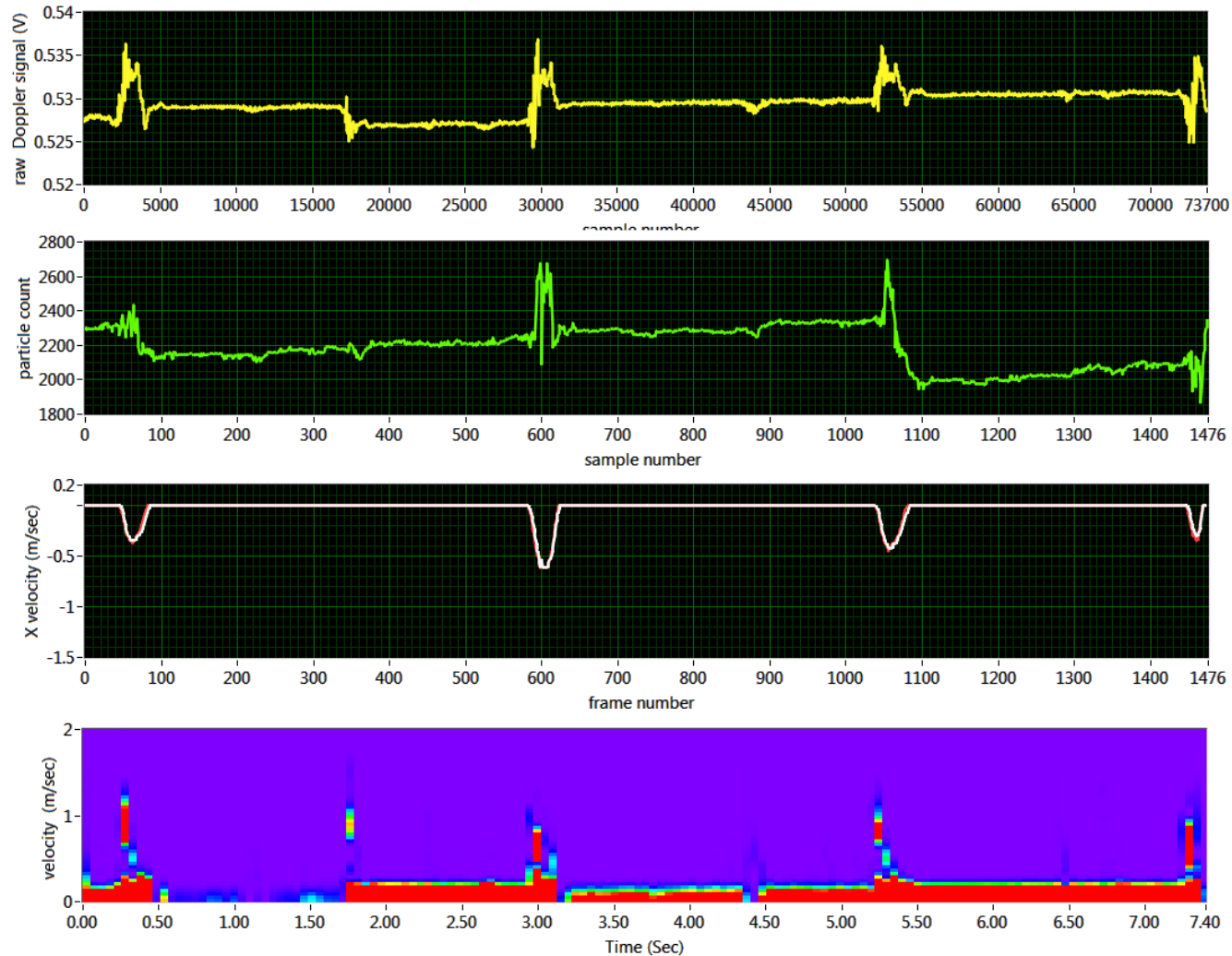
Intermittent Flow monitoring



video

Doppler shift
velocity

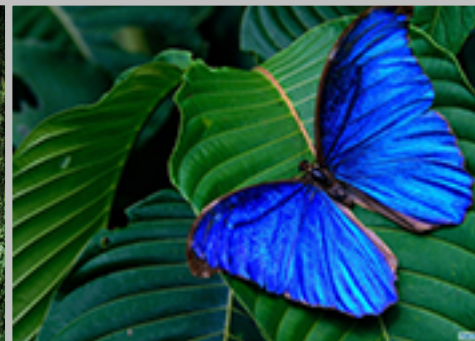
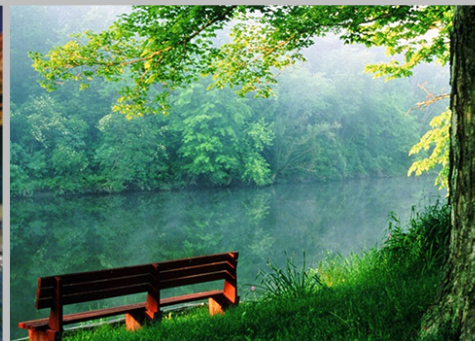
Declining flow rate – still intermittent



- **Microwave Doppler shown to be sensitive to intermittent dense flow, verified with video**
- **Intermittent behavior not observed in pressure data**
- **Potential exists to aid in chemical looping operation**
- **Future work**
 - Refine approach
 - Modify CLR to allow application
 - Examine effect of different particles

This project was funded by the Department of Energy, National Energy Technology Laboratory, an agency of the United States Government. Mr. Charley was funded through a support contract with AECOM, Inc. Dr. Greve was supported in part by through the ORISE Faculty Research Program. Michael Spencer and Richard Stehle were supported through ORISE. Neither the United States Government nor any agency thereof, nor any of their employees, nor AECOM, Inc., nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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