ADVANCED CHARACTERIZATION OF PARTICULATE FLOWS FOR CONCENTRATING SOLAR POWER APPLICATIONS

SETO CSP PROGRAM SUMMIT 2019

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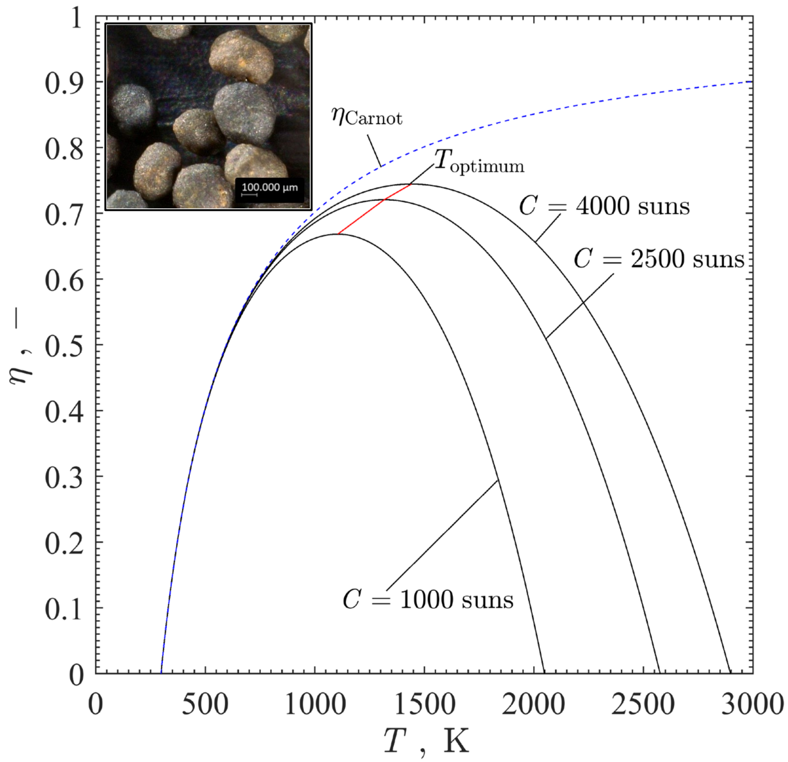
PRESENTATION OUTLINE

- Motivation for characterization of particulate (granular) flows
- Current state-of-the art
- Project outcomes/proposed path
- Recent results
- Summary and conclusions

MOTIVATIONS FOR PARTICULATE HEAT TRANSFER MEDIA IN CSP

Particulate media offers potential advantages over various CSP heat transfer fluids

- Directly irradiated
- Low-cost, abundant media (*e.g.* sand, casting media)
- Higher operating temperatures/ efficiency
- Existing bulk transport, storage technologies
- Various receiver configurations available



Ideal CSP efficiency for various operation temperatures and concentration ratios

$$\eta_{ideal} = \eta_{Carnot} \cdot \eta_{Carnot} = \left(1 - \frac{T_{atm}}{T}\right) \cdot \left(1 - \frac{\sigma T^4}{IC}\right)$$

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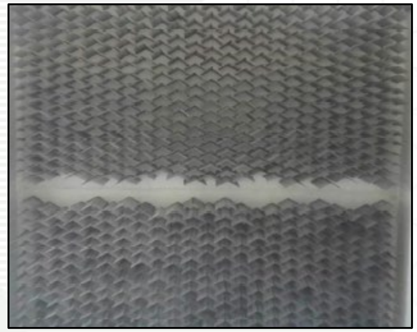
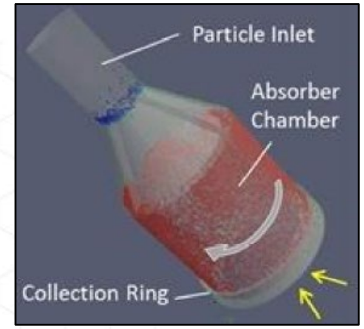
CURRENT SOLAR PARTICLE HEATING RECEIVERS/REACTORS

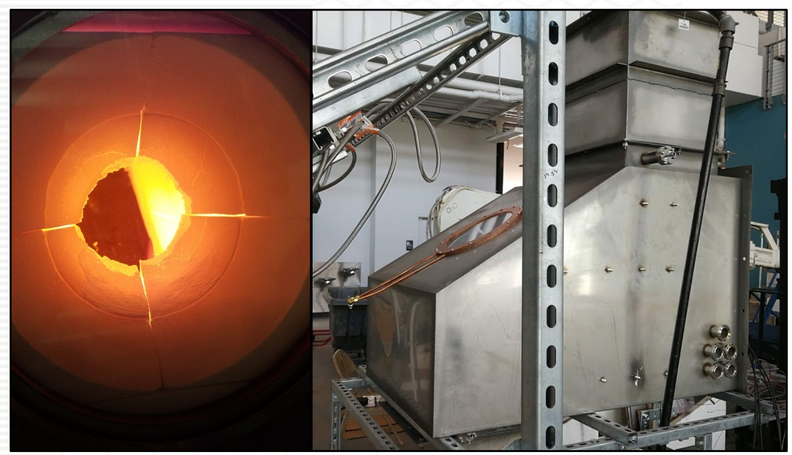
Falling Particle Receiver (SNL)



Obstructed Flow Receiver (GIT/KSU)



Centrifugal Receiver (DLR)

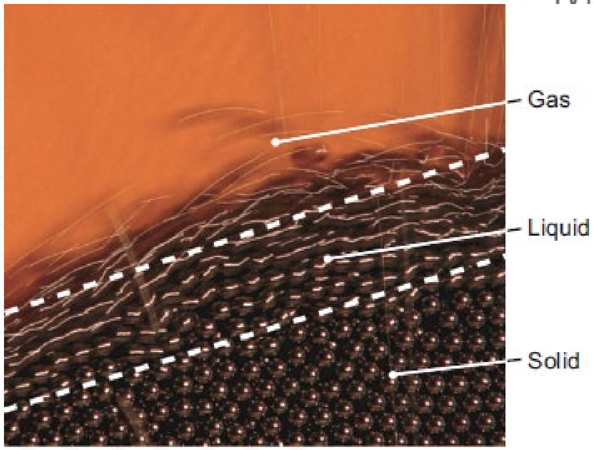


Inclined Flow Receivers / Reactors (GIT)

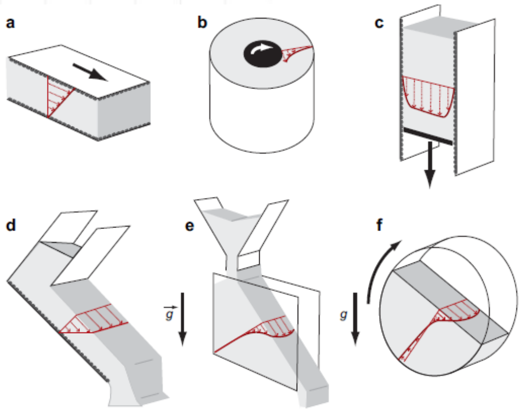
Ho, Clifford K. *Particle Research at Sandia National Laboratories for Concentrating Solar Power.*. United States.

STATE-OF-THE-ART FOR PARTICLE FLOW CHARACTERIZATION

- Bulk particulate transport exhibits traits of solids, liquids, and gases.
- Studies performed for various flow conditions, particulate media to extract bulk transport behavior.
- Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) employed to extract free surface velocity profiles.
- Empirical results inform modeling efforts such as Discrete Element Method (DEM).

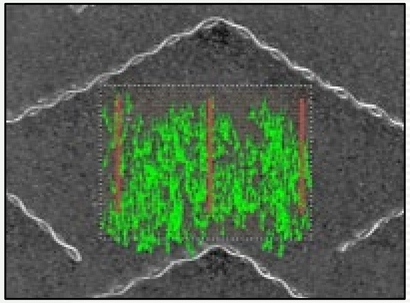


Transitions between particulate flow regimes



Particulate flow geometries studied in previous literature

Extracted velocity vectors for obstructed flow receiver using PIV

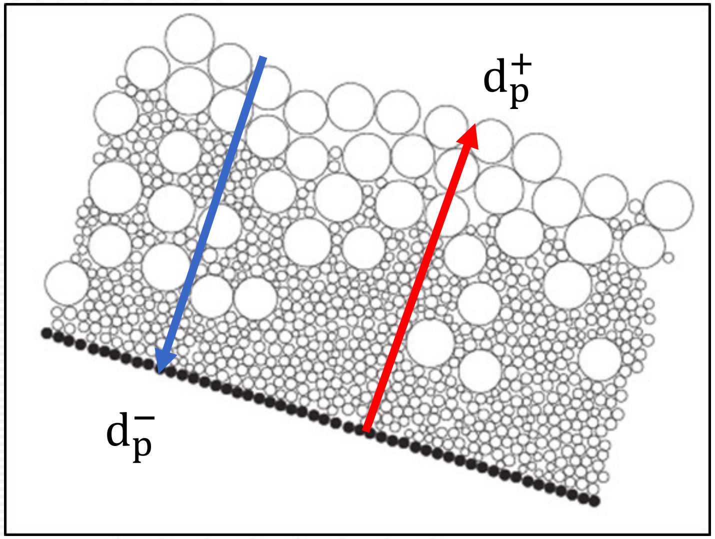


C. K. Ho, J. M. Christian, J. Yellowhair, N. Siegel, S. Jeter, M. Golob, S. I. Abdel-Khalik, C. Nguyen and H. Al-Ansary, AIP Conference Proceedings 1734, 1–8 (2016).

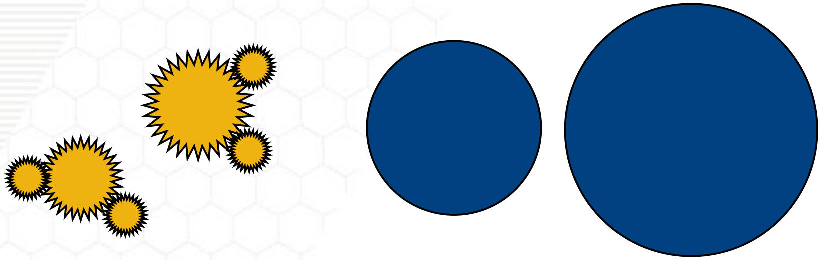
Forterre, Y., & Pouliquen, O. (2008). Flows of dense granular media. *Annu. Rev. Fluid Mech.*, *40*, 1-24.

INFLUENCE OF PARTICLE SIZE, SHAPE, AND MATERIAL PROPERTIES ON BULK BEHAVIOR

- Bulk transport influenced by competing time scales
  - Inter-particle contact time v.s. $\left(\frac{\partial u}{\partial z}\right)^{-1}$
- Bulk transport sensitive to development of small population of long-lived contacts
  - Electrostatic forces
  - Cohesion
  - Particle shape, size interactions
  - Soft particles
  - Temperature effects (*e.g.*, particle softening, agglomeration, thermophoresis)



Particle size segregation for dense flow configurations



Jagged shapes susceptible to long-lived contacts

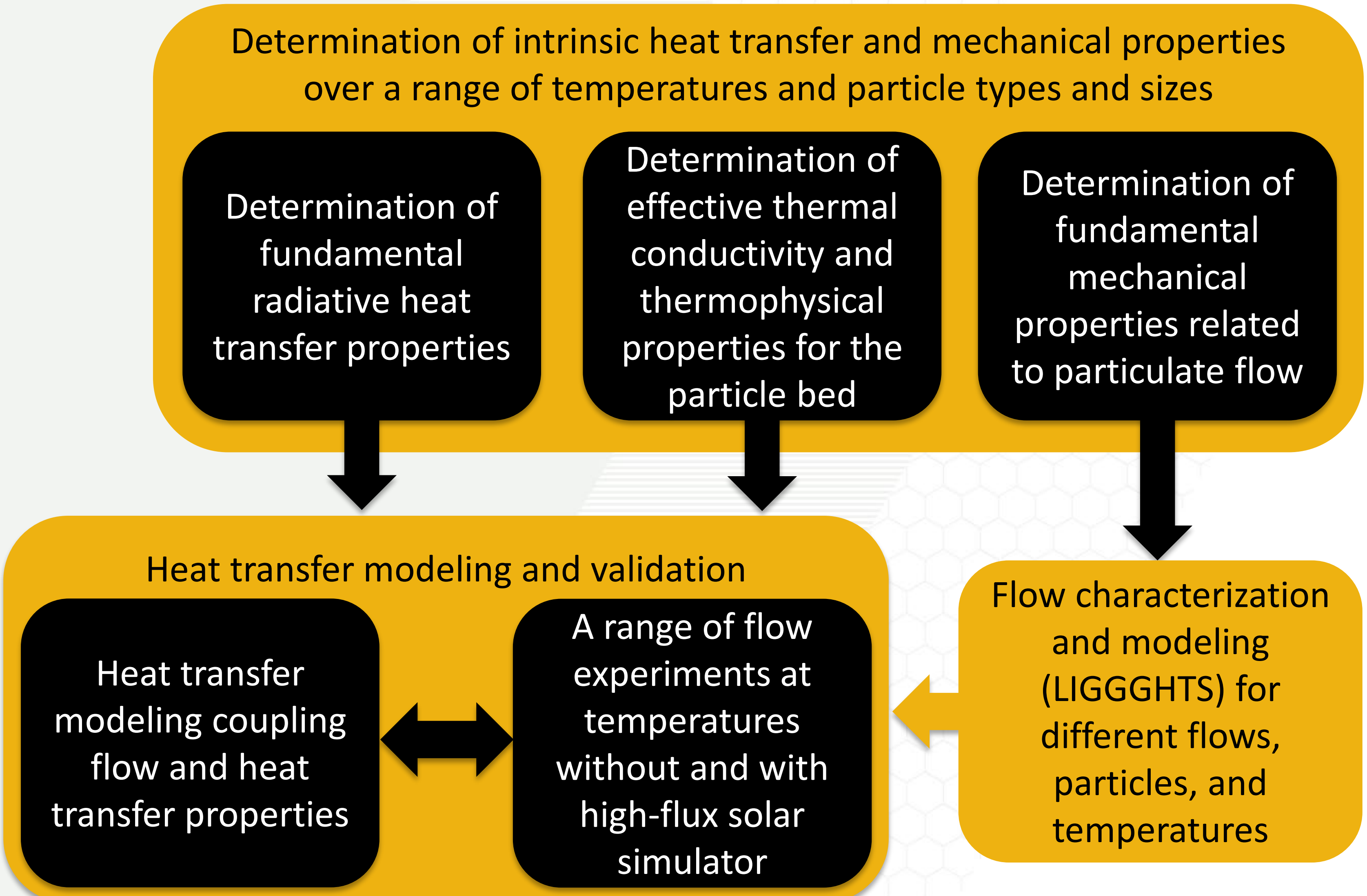
Spherical shapes susceptible to binary particle interactions

Rognon, P. G., Roux, J. N., Naaïm, M., & Chevoir, F. (2007). Dense flows of bidisperse assemblies of disks down an inclined plane. *Physics of Fluids*, *19*(5), 058101.

PROJECT OUTCOMES

Accessible database/publications containing "first-of-their-kind" results related to particulate flows at elevated temperatures as tools to catalyze next generation solar particle heat receivers/reactors:

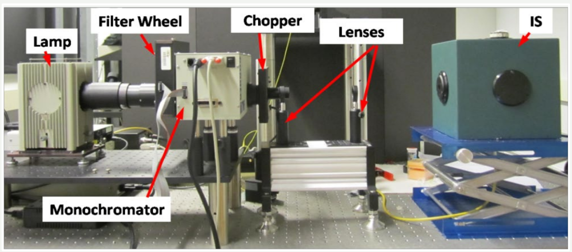
- Intrinsic heat transfer and flow properties for particulate flows for a range of particles
- Particulate flow experiments and models
- Simple to complex experiments for a range of particles, temperatures, and flow configurations
- Validated heat and mass transfer models

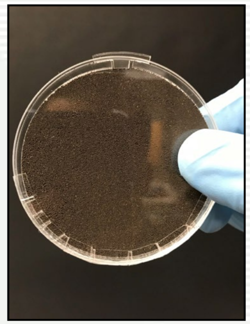

Determination of intrinsic heat transfer and mechanical properties over a range of temperatures and particle types and sizes
Determination of fundamental radiative heat transfer properties
Determination of effective thermal conductivity and thermophysical properties for the particle bed
Determination of fundamental mechanical properties related to particulate flow
Heat transfer modeling and validation
Heat transfer modeling coupling flow and heat transfer properties
A range of flow experiments at temperatures without and with high-flux solar simulator
Flow characterization and modeling (LIGGGHTS) for different flows, particles, and temperatures

RESULTS: DIRECTION, HEMISPHERICAL RADIATIVE PROPERTIES

Monochromator with Integrating Sphere

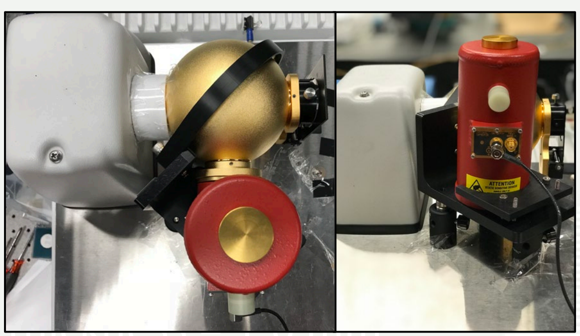
- ❖Quartz window sample holder
- ❖0.38-1.8 µm

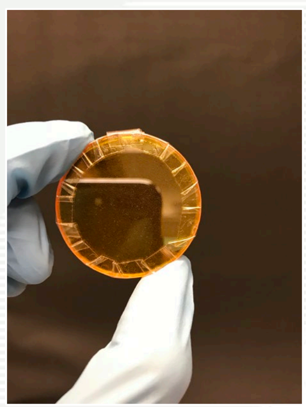


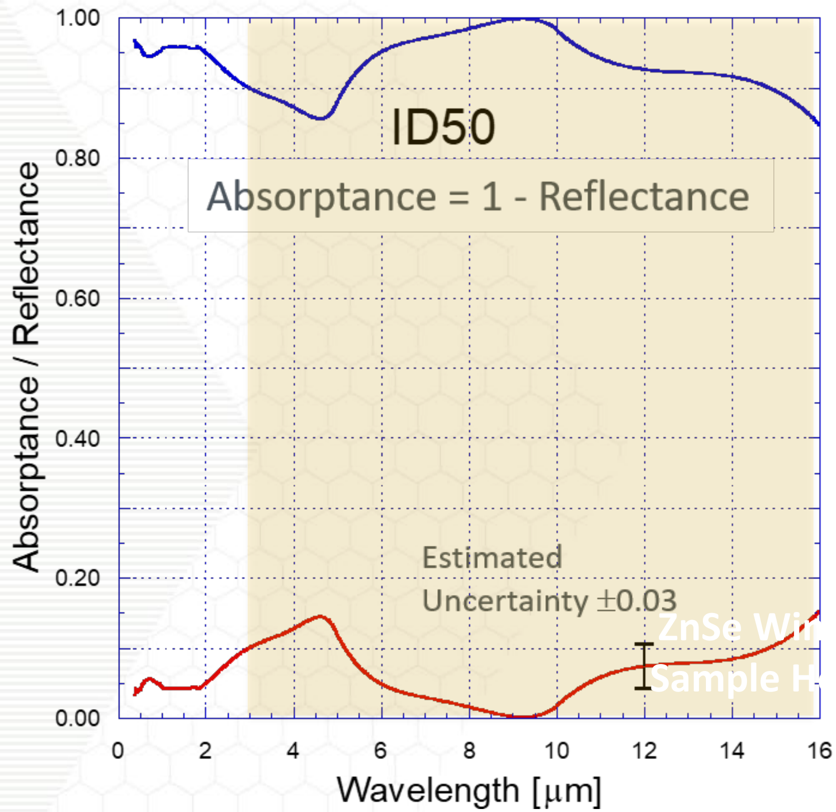


FTIR with Integrating Sphere

- ❖ ZnSe window sample holder
- ❖ 1.8-16 µm







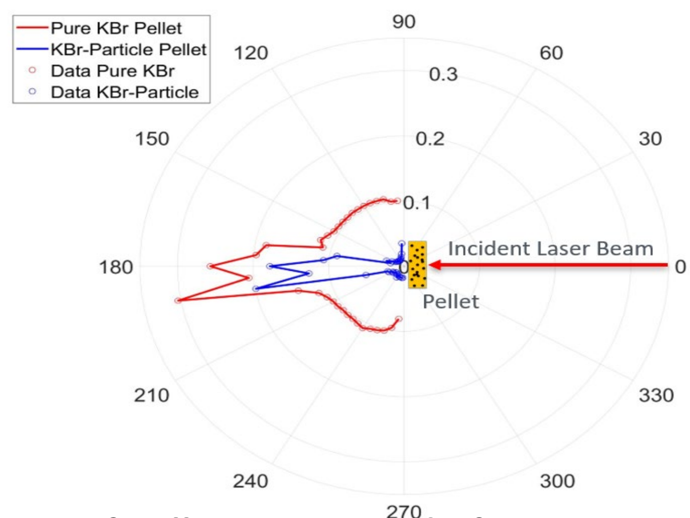
Spectral measurements of the particle bed with reflectance (red) and the absorptance (blue)

RESULTS: SCATTER PHASE FUNCTION SETUP/MEASUREMENTS

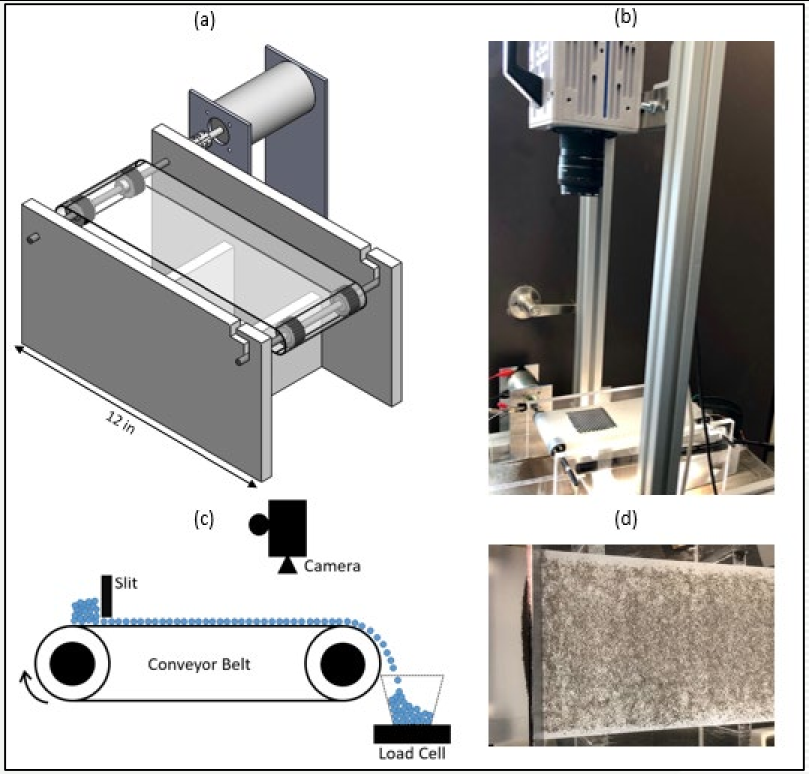
- Three Axis Automated Scatterometer (TAAS)
- Requires particle-KBr pellet
- Laser wavelength: 635 nm
- Pellet fabrication parameters
- 13 mm diameter, ~ 7 ton load compaction, no vacuum, powder pulverized

- Bi-directional Transmittance Distribution Function (BTDF)
- Preliminary results indicate strong forward scattering normal to pellet
- Similar pattern observed for both pellets, uniform decrease due to particles

Fabrication of the KBr pellet with particles: (left) a mixture of KBr powder and ID50 particles; (middle) the 1% by weight KBr-particle pellet after compression; (right) a pure KBr pellet for reference

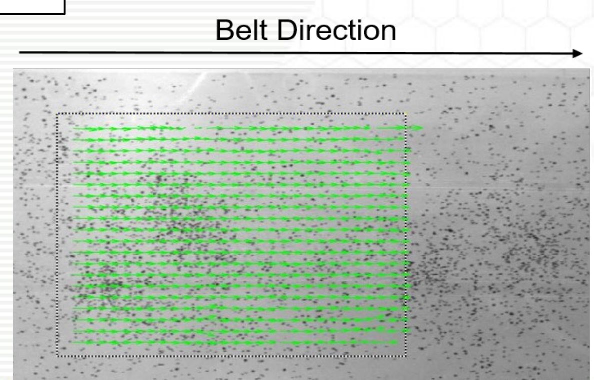


BTDF of pellets composed of pure KBr powder (red) and KBr-particle mixtures of 1 wt% particles (blue)



PIV experimental setup with mass balance pictured with (a) a Solidworks rendering, (b) an image of the high speed camera mounting, (c) a general system schematic, and (d) a view normal to the particle surface

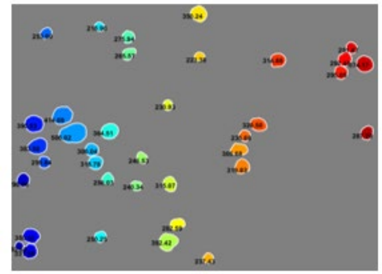
- Experimental setup included conveyor belt with homogeneous, single layer of particles. Belt driven with DC motor, rubber drive rollers
- Tachometer, load cell used to measure rotary shaft angular velocity, particle mass flow rate
- Photron SA3 high speed camera captured particle motion
- Experiment performed using a motor excitation voltage of 2.0 V, camera frame rate of 250 frames/s, and camera resolution of 1024 x 768 pixels
- Velocity field of particulates extracted from post processing, PIVLab

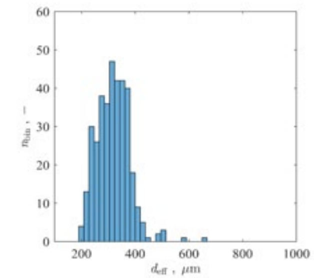


Exported velocity profile of CarboBead CP particulates on conveyor belt processed PIVLab

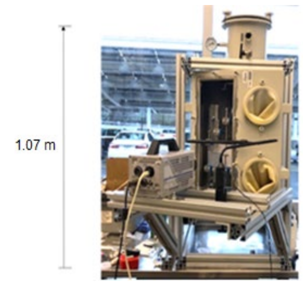
DETERMINING MECHANICAL PROPERTIES UP TO 800 °C

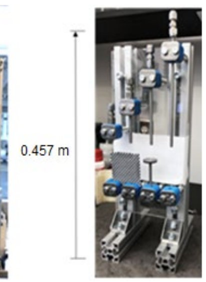
Developed a program to determine particle size distributions and roundness

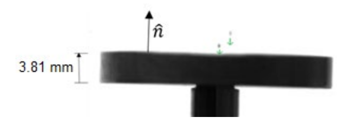




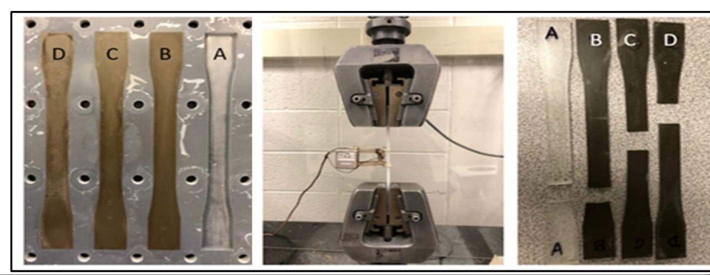
Modified a vacuum chamber coupled to a high-speed camera to measure coefficient of restitution







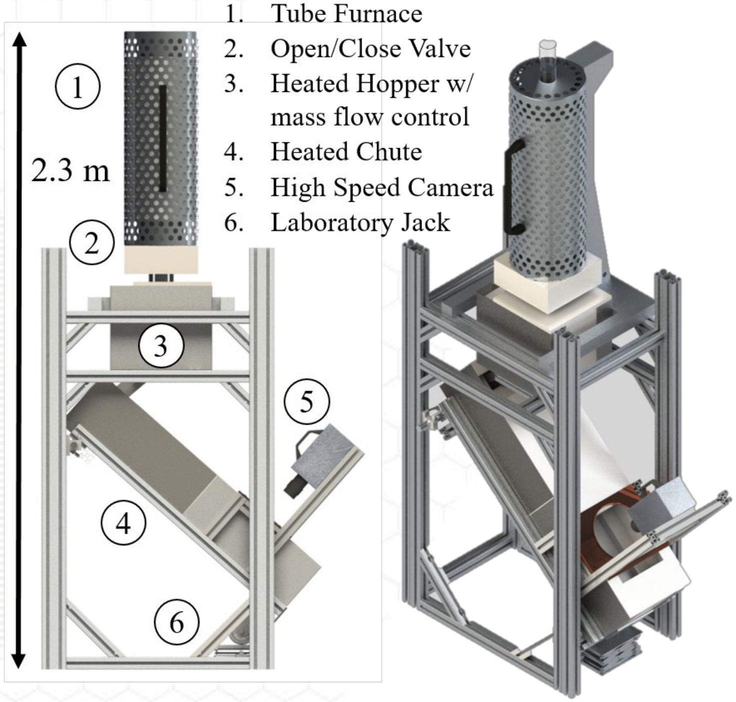
Developing protocols with tensile tests to determine modulus of elasticity and Poisson's ratio



Developing a slip-stick apparatus to measure static and dynamic coefficients of friction

MODIFYING A TILT FLOW RIG FOR FREE FLOW AND ELEVATED TEMPERATURES

- Room-temperature tilt rig modified for high temperature operation
- Various inclination angles / flow conditions, mass flow rates, plane lengths, temperatures
- Carbolite Gero EVT 12-600 Split Tube furnace for particle heating
- Mass flow rate controlled by Beverloo plate, hopper
- Kanthal Moduthal heating module guard heaters, maintain particle temperature
- Particles observed through water-cooled quartz window using high-speed and IR cameras



Solidworks rendering of modified inclined-flow experimental rig with important features labeled and viewed from various angles

SUMMARY AND CONCLUSIONS

❖ We have proposed to extend the state-of-the-art for particulate flows related to CSP.

❖ The proposed work addresses a **significant** gap related to particulate flows at elevated temperatures.

❖ The initial results are very promising with the methodology coming into place to disseminate results to CSP research community.

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- Research Engineer: Matthew Golob
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