GENERAL PROJECT OVERVIEW

Determination of intrinsic heat transfer and flow properties over a range of temperatures and particle types and sizes

- Determination of fundamental radiative heat transfer properties
- Determination of 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 irradiation

Flow characterization and modeling (LIGGGHTS) for different flows, particles, and temperatures
Accessible database/publications containing “first of their kind” results related to particulate flows as tools to catalyze next generation solar particle heat receivers/reactors:

- Intrinsic radiative heat transfer and flow properties for granular flows for a range of particles
- Granular flow experiments and models
- Simple to complex experiments for a range of particles, temperatures, and flow configurations: Inclined flow → vertical flow between parallel plates → stairstep flow → flow exposed to high radiative fluxes (high-flux solar simulator)
- Validated heat and mass transfer models
PARTICLES CHARACTERIZED

Carbobead CP
Carbo HSP
Wedron SiO₂
PARTICLE PREPARATION

- Intrinsic properties measured using hot-pressed, machined plates
  - Elastic properties
  - Sliding/rolling surface for friction coefficients
  - Impact plane for coefficient of restitution
- Flour for Carbo HSP jet-milled with collaboration with SNL
- Silica flour obtained from NREL

Jet-mill → Flour → Hot-press → Hot-pressed plate → Machine → Specimens of different geometries
FLOW PROPERTY DETERMINATION

Developed a program to determine particle size distributions and roundness

Particle drop setup coupled to a high-speed camera to measure coefficient of restitution

Used a slip stick method mounted in a high-temperature furnace to measure static and rolling friction

Determined elastic and shear moduli using impulse excitation for different temperatures
Particle tape method
- More stable method due to constant areal fraction throughout the measuring period.
- Additional factors (e.g., scattering and absorption by the tape) need to be accounted for the analysis.
- Pure scattering data of the particle can be obtained by subtracting the scattering measurement of tape.

Particle curtain method
- A direct way to obtain scattering property without introducing other measurement uncertainties.
- Flowing nature of the particles makes the measured signal unstable and long sampling period is required.
**RADIATIVE MEASUREMENT SETUP**

**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

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**Quartz Window Sample Holder**
- Particle Beds
- Various thicknesses
- Cover plates
- Thickness = 1.6 mm

**ZnSe Window Sample Holder**
- Particle Bed
- Thickness = 6.35 mm
- Cover plates Thickness = 3.0 mm

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**Sample Holder Design**
TILT FLOW RIG

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

1. Tube Furnace
2. Open/Close Valve
3. Heated Hopper w/ mass flow control
4. Heated Chute
5. High Speed Camera
6. Laboratory Jack

Vertical plate flow setup

Design of stair-step flow geometry
EXPERIMENTAL RESULTS

- Experiment performed using Carbobead CP 30/60
- Particles heated to 600 °C in tube furnace and released onto inclined plane (27° inclination)
- Bulk surface $V_{\text{inlet}} = \sim 0.07 \text{ m/s}$, $V_{\text{outlet}} = \sim 0.09 \text{ m/s}$
- Bulk surface $T_{\text{inlet}} = \sim 560 \degree \text{C}$, $T_{\text{outlet}} = \sim 525 \degree \text{C}$
- Boundary conditions from experiment to be incorporated in flow and heat transfer models
SUMMARY AND CONCLUSIONS

- Our project has focused on addressing a significant gap related to granular flows at elevated temperatures.

- Radiative heat transfer properties have been measured to determine volume-averaged extinction and scattering coefficients for different flows to inform heat transfer modeling.

- Flow properties coupled to experimentation at elevated temperatures for a range of flow configurations and modeling granular flows and heat transfer have highlighted the impact of temperature on these flows with strong evidence that this must be considered in the design of solar particle heating receivers/reactors and related flow infrastructure.

- Our updated database and publications of our work outline these changes and provide a basis for the design of the next generation of CSP coupled to particle-based thermal energy storage.
  - http://hdl.handle.net/1853/62903
  - http://hdl.handle.net/1853/63725
  - We have a dropbox with preliminary results that may be made available.
ACKNOWLEDGEMENTS

• Funding from the Solar Energy Technologies Office: DE-EE0008372
• SETO Technology Managers: Matthew Bauer and Andru Prescod
• Graduate Research Assistants: Malavika Bagepalli, Chuyang Chen, Shin Young Jeong, Andrew Schrader, and Justin Yarrington
• Research Engineers/Postdoctoral Researchers: Matthew Golob, Gokul Pathikonda, Joshua Brooks
• Advisory Board: Hany Al-Ansary (KSU), Klaus Brun (Elliot Group), Cliff Ho (SNL), Sheldon Jeter (GIT), and Zhiwen Ma (NREL), and Todd Otanicar (Boise State)
HIGH-FLUX SOLAR SIMULATOR

- Seven 6 kWₑ xenon arc lamps
- Mounted in truncated ellipsoidal reflectors
- Capable of focusing intense irradiation (i.e., ~5000 kW·m⁻²) over a 40 mm diameter with a similar spectral distribution as the sun
- Allows for reproducible experimentation and the inputs can be varied by varying lamp power
HIGH-TEMPERATURE EMISSOMETER

- Up to 750 °C
- Near normal emittance of particle beds
- 2 – 16 mm.