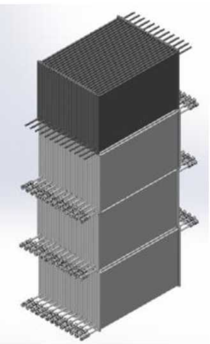
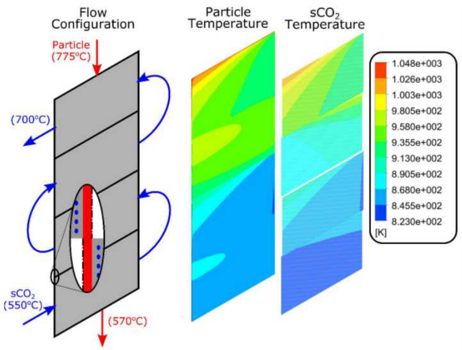
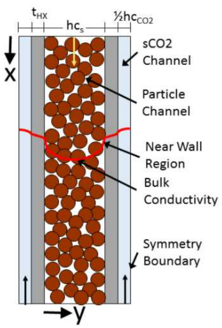
SAND2018-6953C

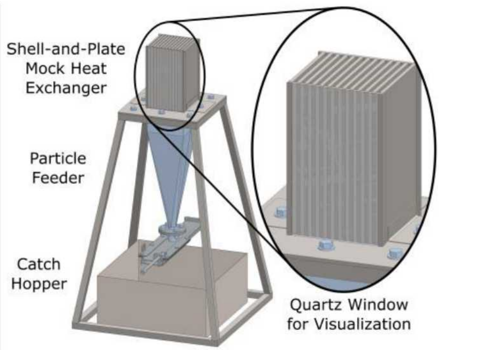
Exceptional service in the national interest

Sandia National Laboratories









Efficient Modeling and Analysis of a Moving Packed-Bed Particle-to-sCO_2 Heat Exchanger

Kevin J. Albrecht and Clifford K. Ho

Sandia National Laboratories, Concentrating Solar Technologies (8823)

PowerEnergy2018-7324, SAND2018-####

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

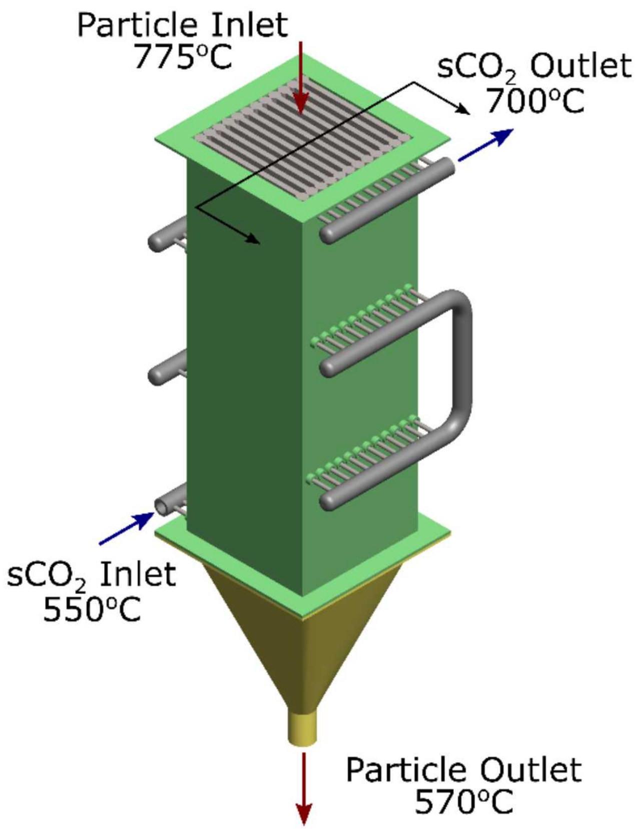
- Introduction/Objectives
- Heat Exchanger Modeling
- Heat Exchanger Design Considerations
- Conclusion/Future Work

Outline

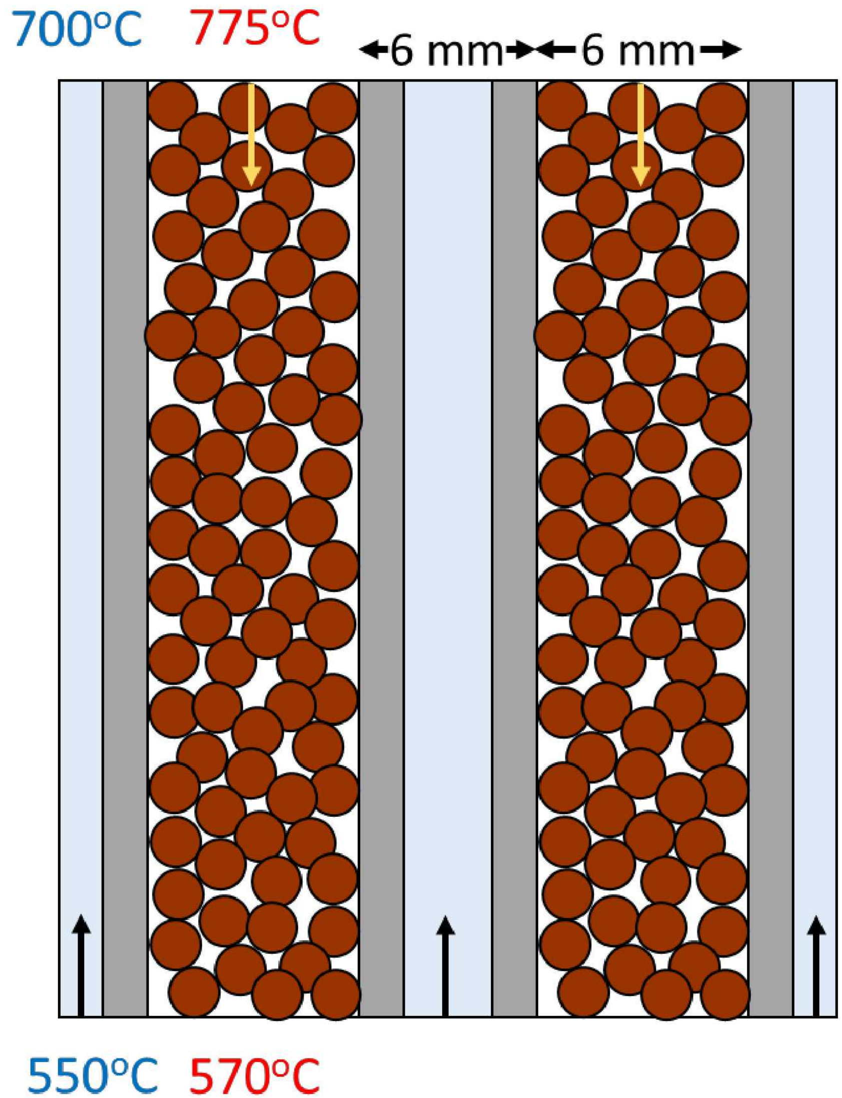
- Introduction/Objectives
- Heat Exchanger Modeling
- Heat Exchanger Design Considerations
- Conclusion/Future Work

Particle receiver development has led to the need for an sCO_2-to-particle heat exchanger

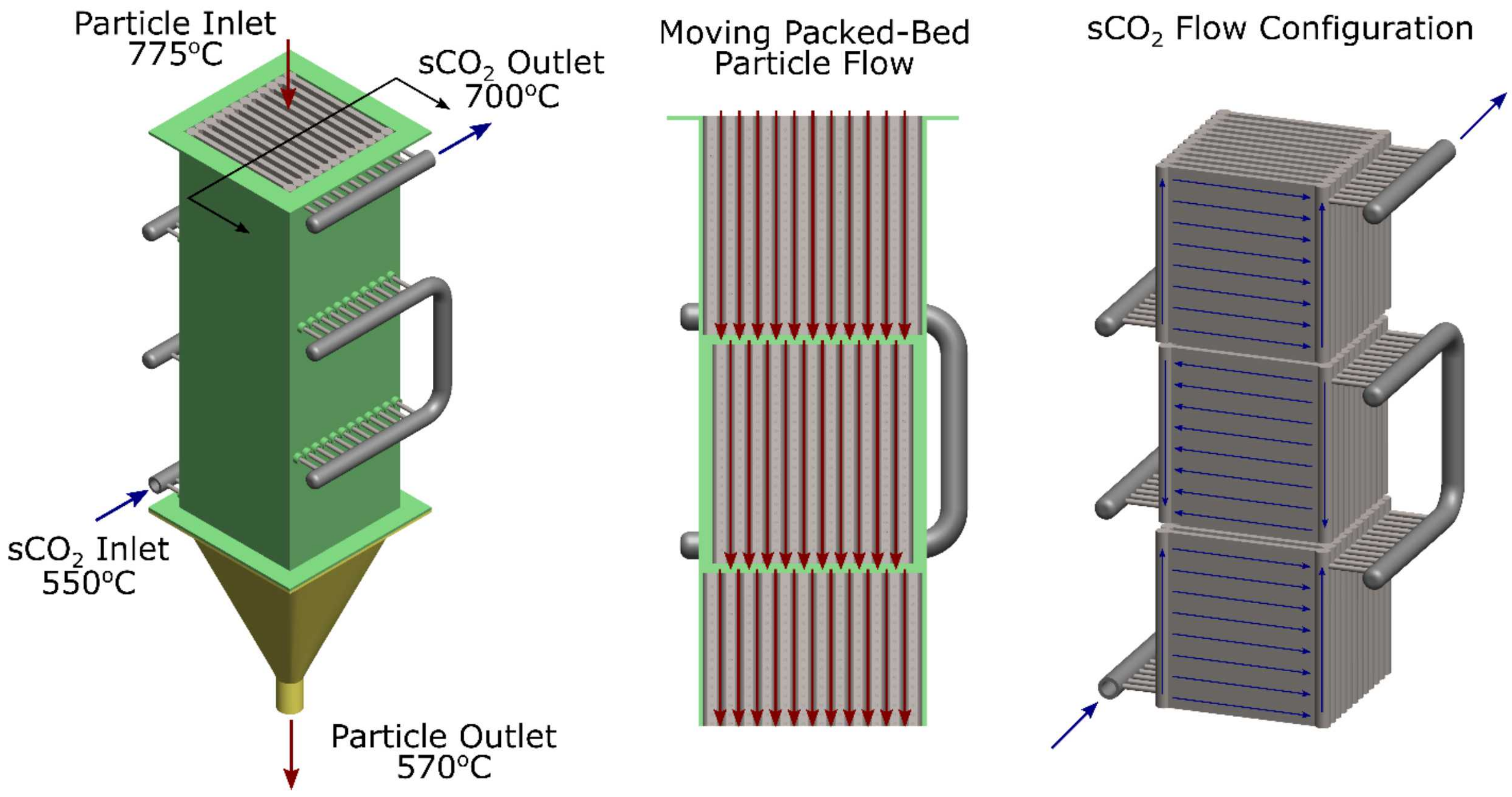
- Particle-based CSP plants enable the use of sCO_2 power cycles
- Multiple particle receivers have been demonstrated at the megawatt scale
- Minimal work has been conducted on particle-to-sCO_2 heat exchangers



Shell-and-plate moving packed-bed heat exchanger configuration

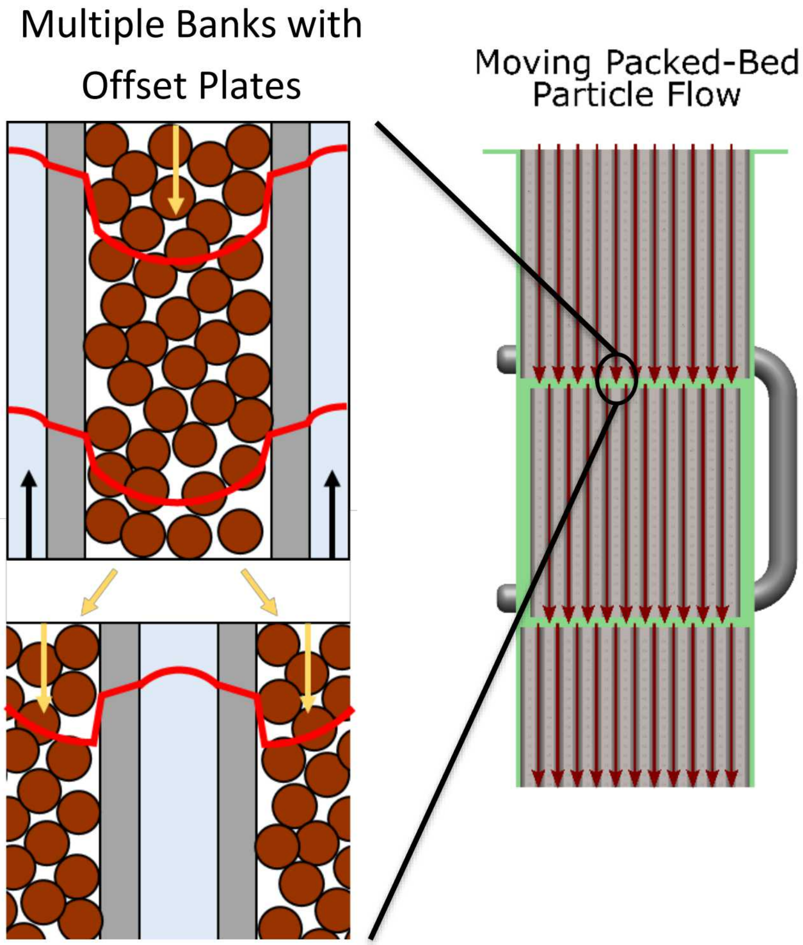


Moving Packed-Bed Heat Exchanger Geometry



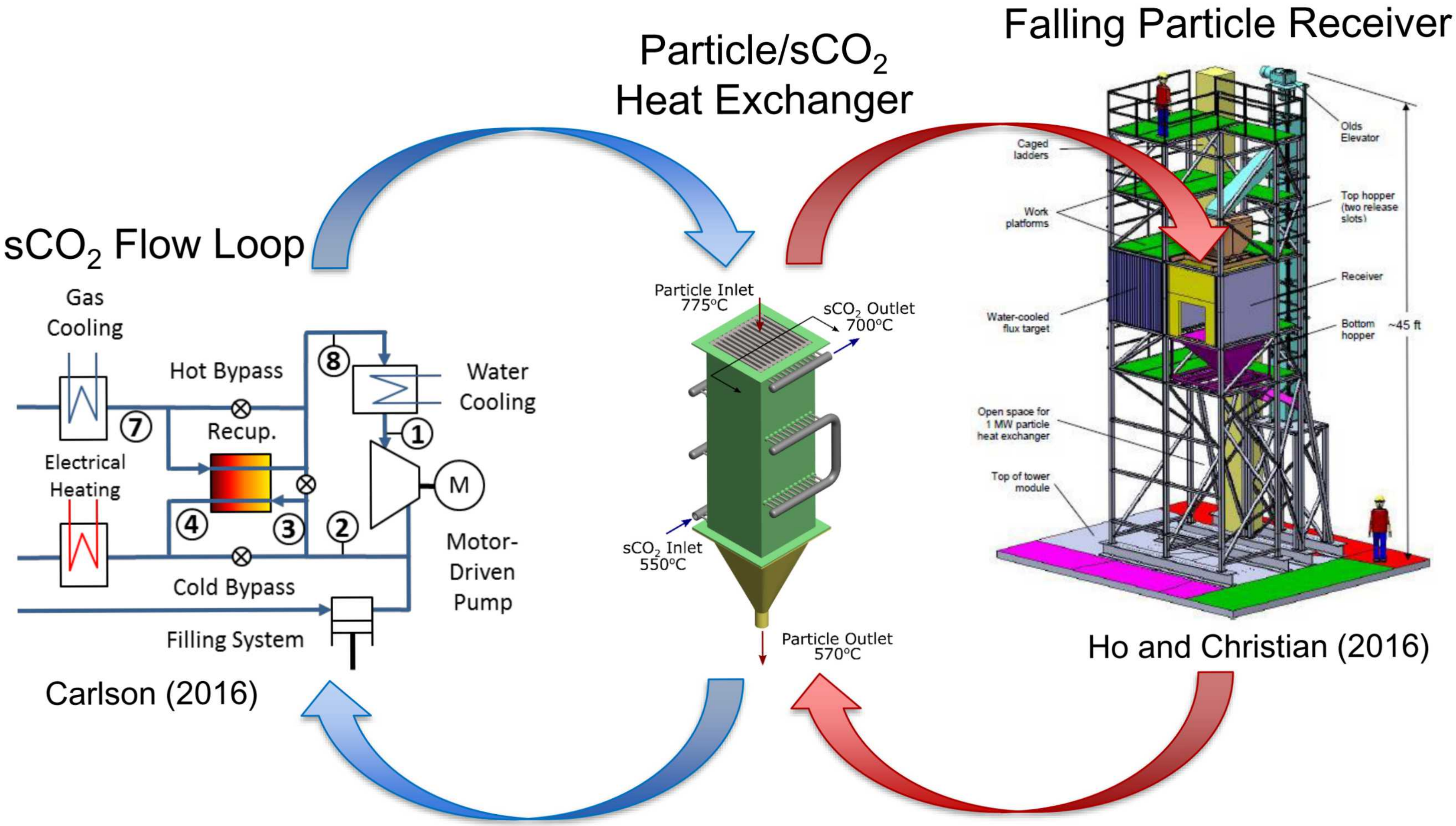
- Constructed from multiple cross-flow banks arranged in a counter-flow configuration

Multibank approach allows for particle heat transfer enhancement



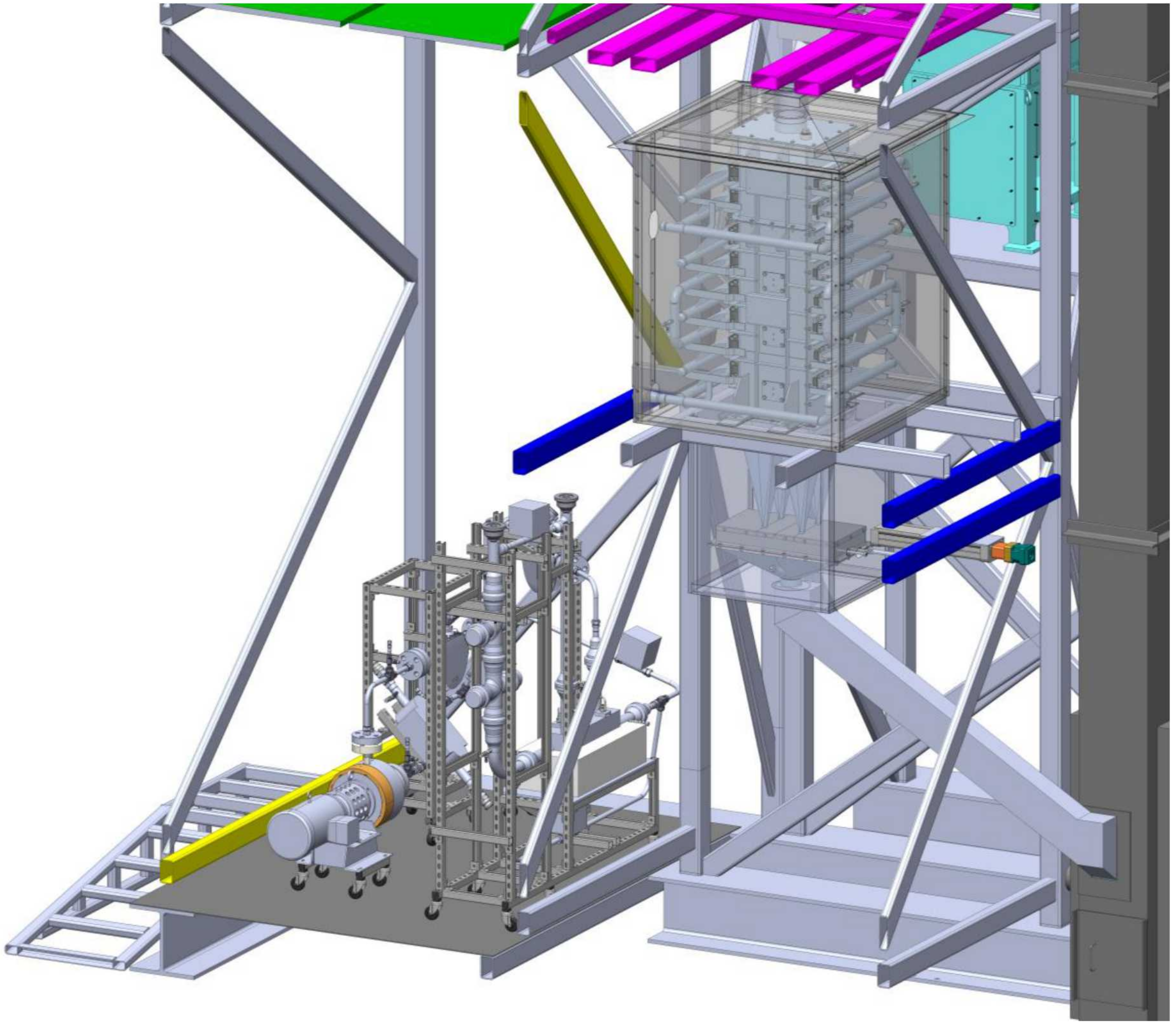
- Multibank configuration allows for cross-channel mixing and multiple thermal entries

Objective



- Develop and test 100kW$_{th}$ prototype particle-to-sCO_2 heat exchanger

100 kW_t heat exchanger and sCO_2 flow loop integrated with falling particle receiver module

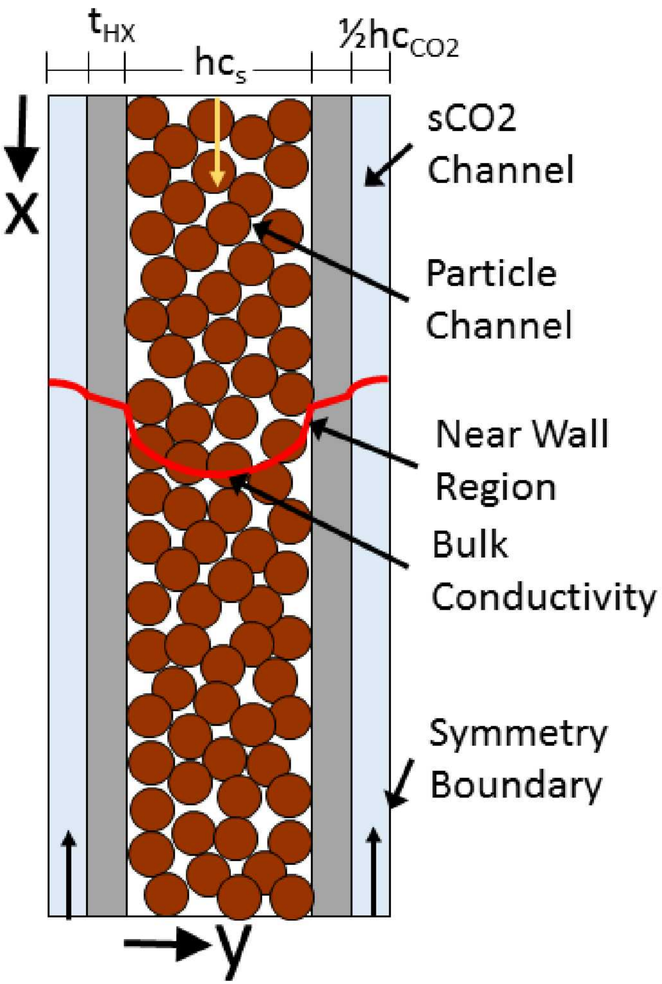


- Heat Exchanger to be commissioned in late summer 2018

Outline

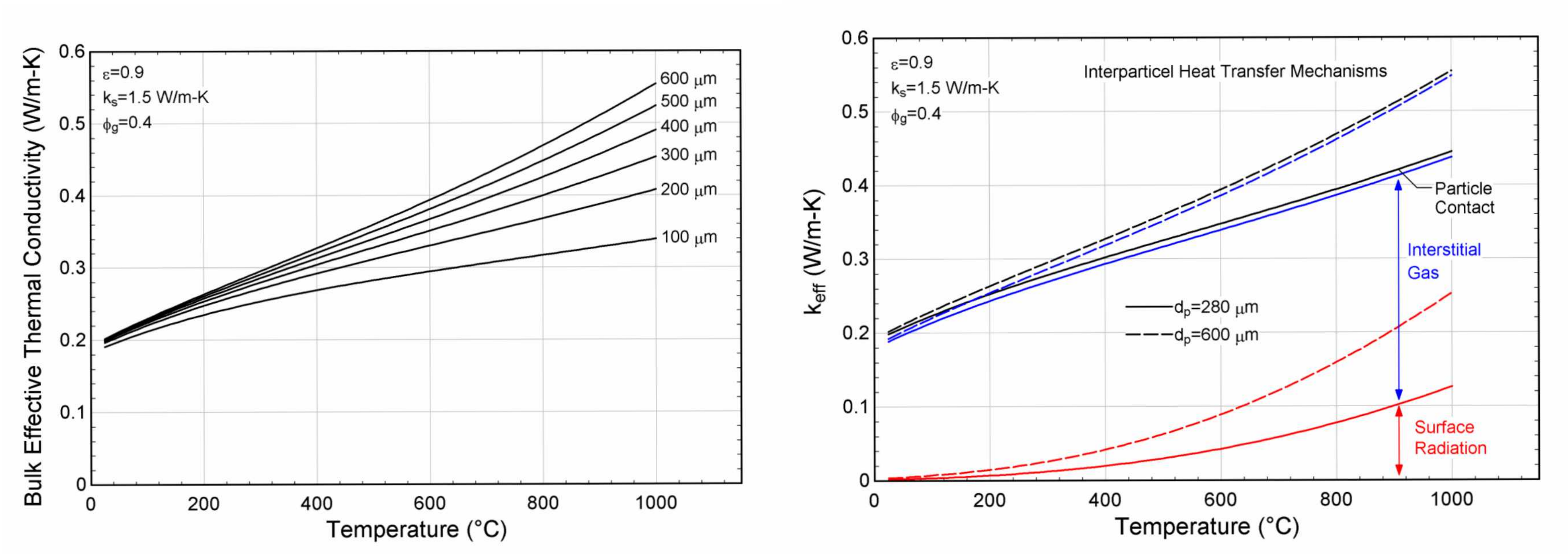
- Introduction/Objectives
- Heat Exchanger Modeling
- Heat Exchanger Design Considerations
- Conclusion/Future Work

Moving Packed-Bed Heat Transfer Modeling



- Correlations required to predicted thermal resistance in near-wall region
- Thermal transport in particle packed bed is characterized with bulk effective thermal conductivity
- Couple particle and sCO_2 domain temperature profiles

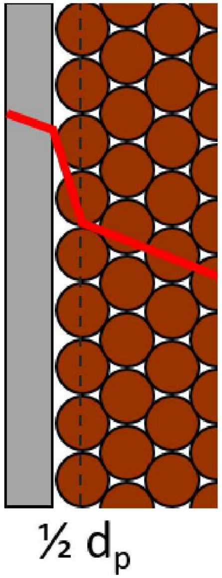
Contributions to Effective Packed-Bed Thermal Conductivity



- Packed-bed thermal conductivity rises with temperature due to increased conductivity of the gas phase and radiation contributions
- Particle diameter has a large impact on thermal conductivity at elevated temperature due to radiation

W. van Antwerpen, C. G. du Toit and P. G. Rousseau, "A review of correlations to model the packing structure and effective thermal conductivity in packed beds of mono-sized spherical particles," Nuclear Engineering and Design, vol. 240, no. 7, pp. 1803-1818, 2010.

Particle packing in the near-wall region increases thermal resistance



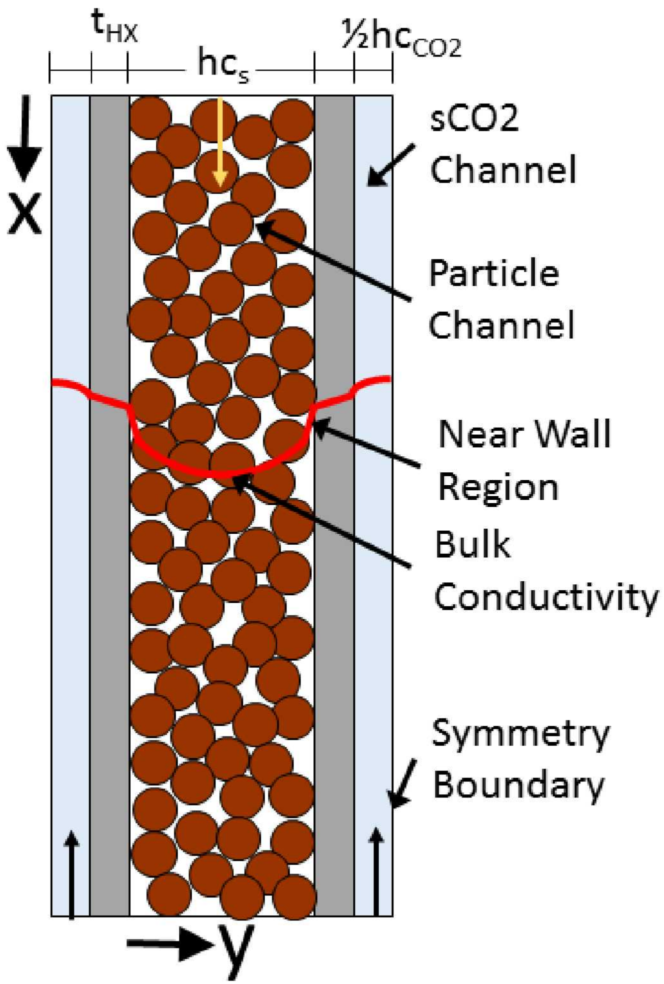
$$\phi_{g,nw} = \frac{\left(1-\phi_g\right)\left(0.7293+0.5139Y\right)}{1+Y}$$

$$R_c'' = \frac{d_p}{2k_{s,nw}^{eff}}$$

J. M. Botterill and A. O. Denloye, "A Theoretical Model of Heat Transfer to a Packed or Quiescent Fluidized Bed," *Chemical Engineering Science,* vol. 33, no. 4, pp. 509-515, 1978.

- Particle packing in near wall region results in high void fractions and reduced effective thermal conductivity
- Resistance is considered to be ½ particle diameter

2-D Single Component Continuum Modeling Approach



<u>2D S.S. Particle Conservation of Energy:</u>

$$\rho_s v_s c_{p,s} \frac{\partial T_s}{\partial x} = \frac{\partial}{\partial y}\left(k_{s,eff} \frac{\partial T_s}{\partial y} \right)$$

<u>1D S.S. sCO2 Conservation of Energy:</u>

$$\rho_{CO_2} v_{CO_2} c_{p,CO_2} \frac{dT_{CO_2}}{dx} = \frac{2q''}{h_{CO_2}}$$

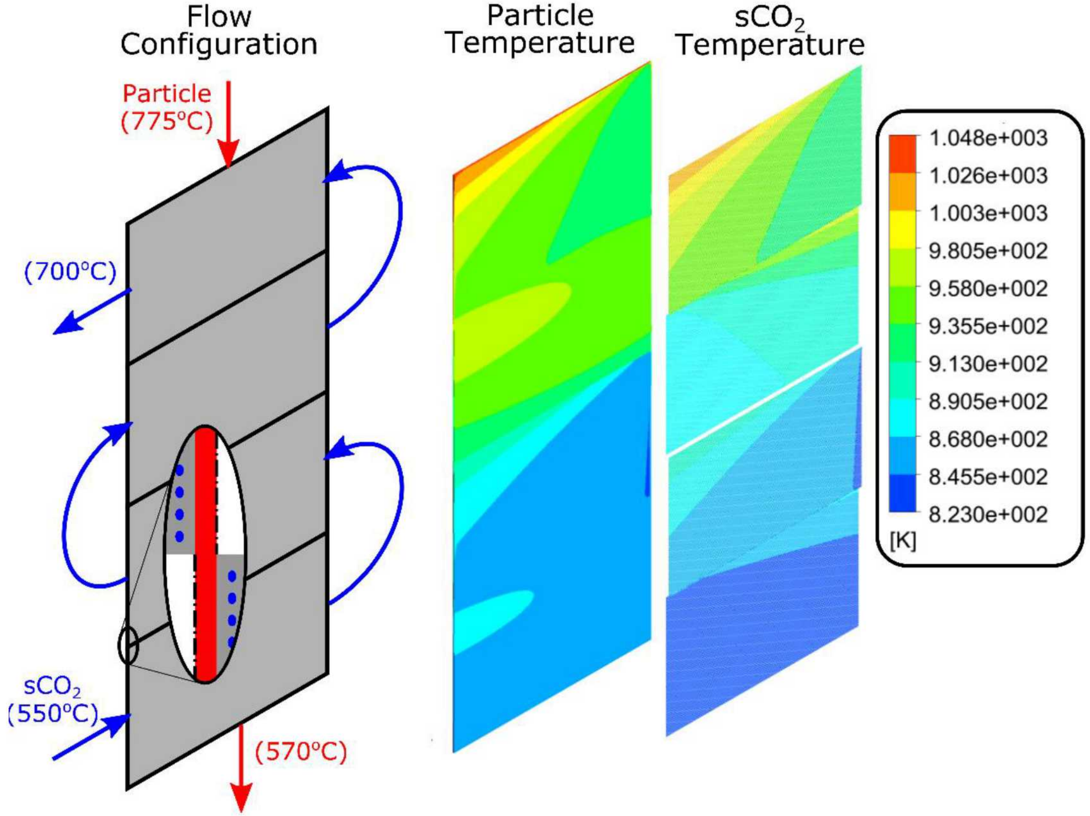
<u>Regions Coupled Through Resistive Network:</u>

$$q''(x) = k_{s,eff} \left.\frac{dT_s}{dy}\right|_{0,x} = \frac{1}{R''}\left(T_s(0,x) - T_{CO_2}(x) \right)$$

$$R''(x) = R''_c + \frac{t_{HX}}{k_{HX}} + \frac{1}{h_{CO_2}}$$

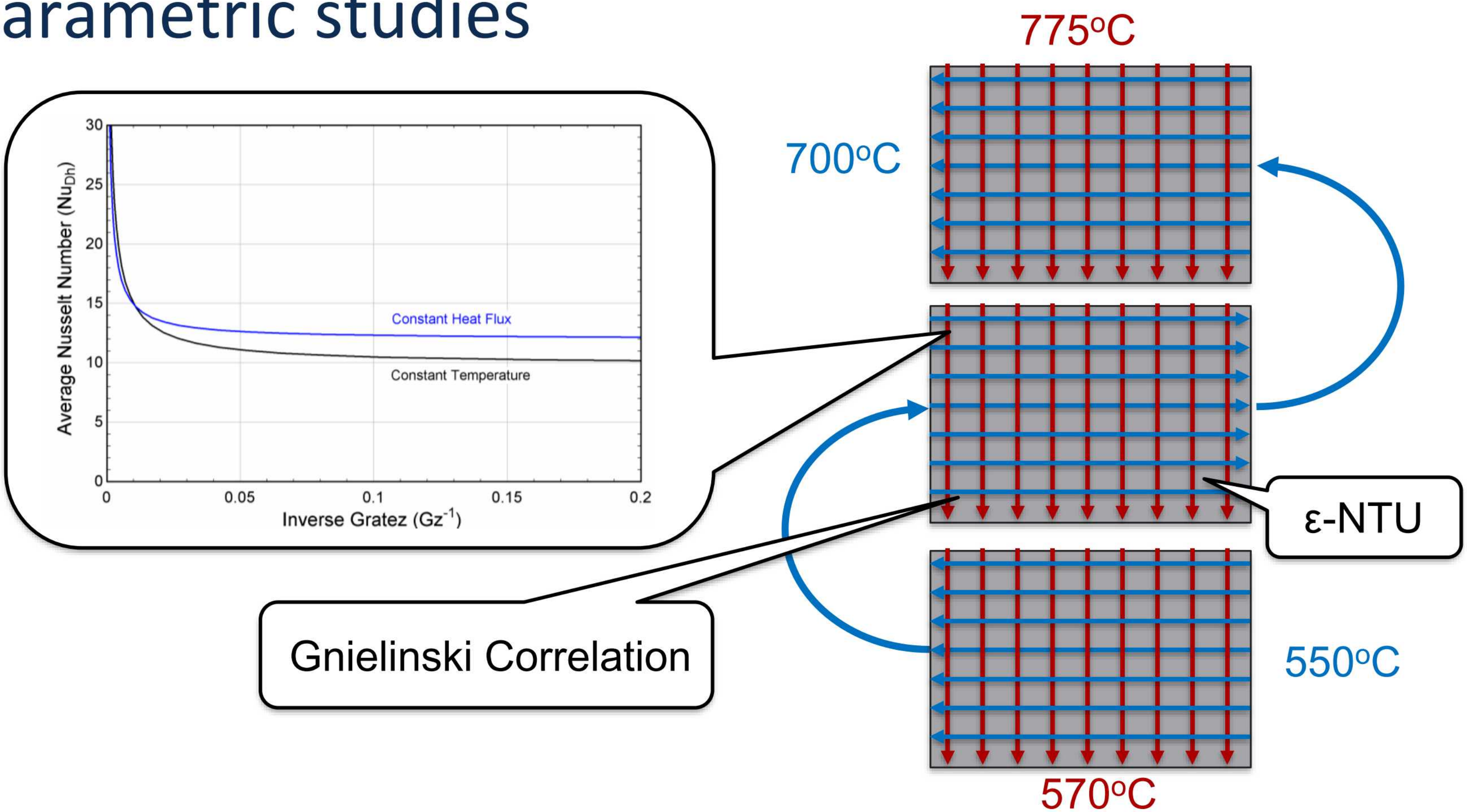
- Does not capture cross/counter flow limitations or plate geometry

CFD Codes with closure relationships can be used to predict overall heat transfer coefficient



- CFD proved to be too computationally intensive for large parametric studies
- Model is still useful for prototype design, thermomechanical analysis and transient simulation

Simplified modeling methodology for parametric studies

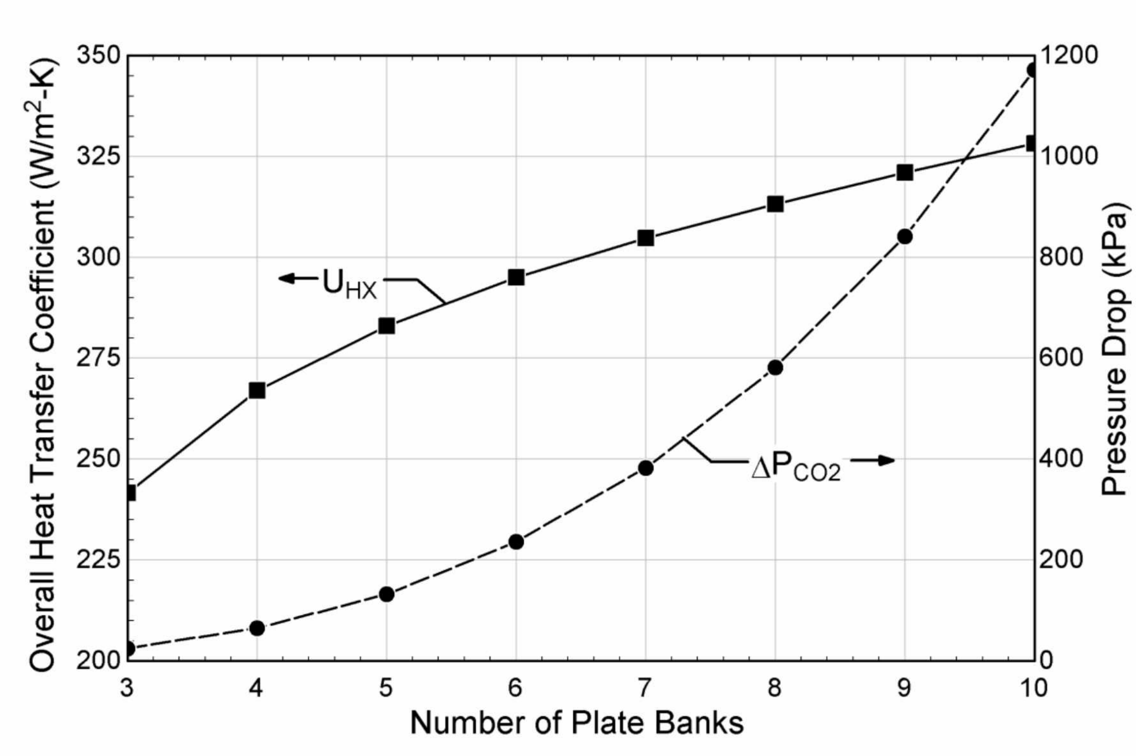


- Effectiveness-NTU correlations to capture flow configuration
- Correlations for particle-wall and sCO_2-wall convection coefficient
- Link bank inlets and outlets in counter-flow configuration

Outline

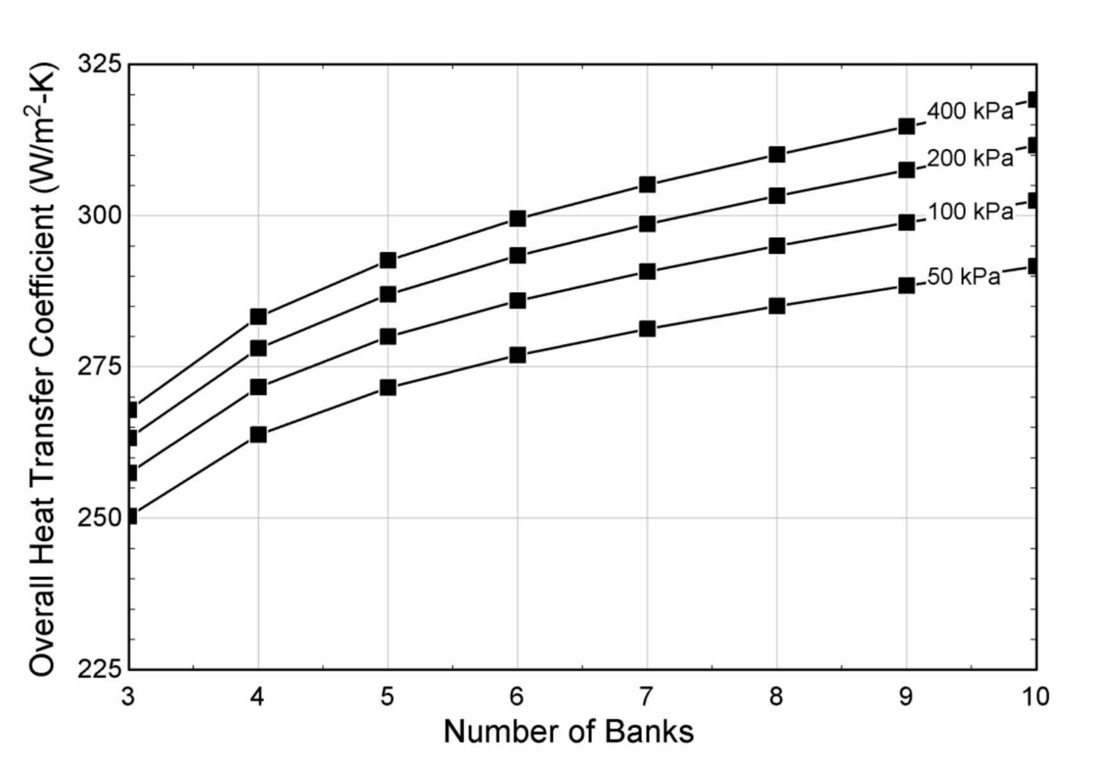
- Introduction/Objectives
- Heat Exchanger Modeling
- Heat Exchanger Design Considerations
- Conclusion/Future Work

Increasing the number of plate banks improves the overall heat transfer coefficient



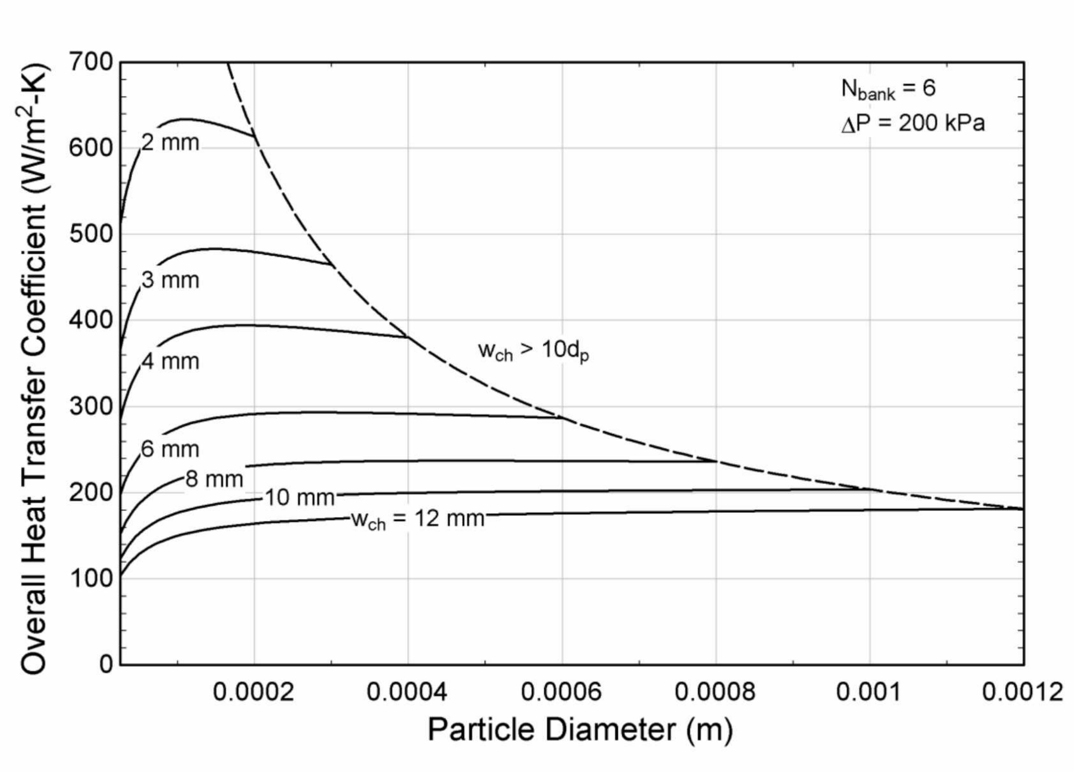
- Increasing the number of cross-flow banks allows for more cross-channel mixing to increase particle side heat transfer
- Increased pressure drop results from additional banks with fixed sCO_2 channel geometry

Comparison of palate banks with constant sCO_2 pressure drop



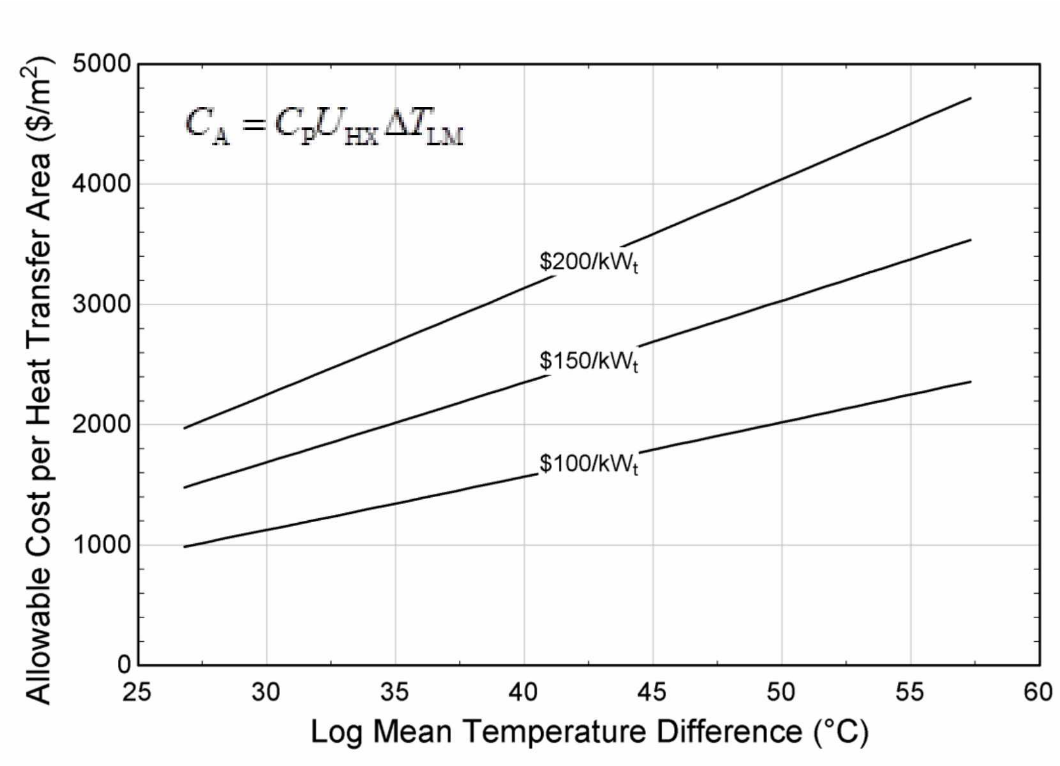
- Constant sCO_2 pressure drop reduces the overall heat transfer coefficient improvement from increasing number of banks

Influence of Particle Size and Plate Spacing



- Smaller channel width improve heat transfer due to shorter heat diffusion lengths
- Smaller particle diameters are favored in smaller channels due to particle-wall contact resistance becoming limiting

Primary Heat Exchanger Cost Considerations



- Performance, operating conditions, and cost targets determine allowable cost of heat transfer surface area
- SunShot 2020 cost targets for power cycle heat addition are \$150/kW$_t$, which requires heat transfer surface area below \$2400/m^2
- Full technoeconomic analysis needed to optimize operating conditions and full plant design

Conclusion

- Avenues for improving moving packed-bed heat exchanger performance identified
  - Plate spacing reduction, corresponding particle size reduction, and increased number of banks
- Average particle-wall heat transfer coefficients approaching 400 W/m^2-K are possible with channel dimensions of 4 mm
- Coupled technoeconomic study with predictive models of moving packed-bed heat exchanger and falling particle receiver is needed
- Future work:
  - Heat exchanger 100 kW prototype will be commissioned in August and allow for model validation
  - Particle size distribution for reduced near wall thermal resistance

Acknowledgements

- Ashley Byman and Robert McGillivray of Solex Thermal Science
- This work was supported by the DOE SunShot Program (SuNLaMP-0000000-1507)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Plate Geometry