Narrow-Channel, Fluidized Beds for Effective Particle Thermal Energy Transport and Storage

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knowledgements of Collaborators and Funding

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ny at Mines currently contribute to particle-O$_2$ HX development:

- urrent Contributors – Research Assoc. **Jesse Fosheim**, rof. Ivar Reimanis, Students: Winfred Arthur-Arhin, Azariah hompson, Yahya Bokhary, Julia Billman

rrent Collaborators on particle-sCO$_2$ HX velopment

- **andia National Laboratories** – **Kevin Albrecht**, Chris owen, Andrea Ambrosini
- **ARBO Ceramics** – Brett Wilson

evious collaborations

- **REL**– Zhiwen Ma, Janna Martinek, Judy Netter
- **rayton Energy –** Bill Caruso, Megan Kirschmeier

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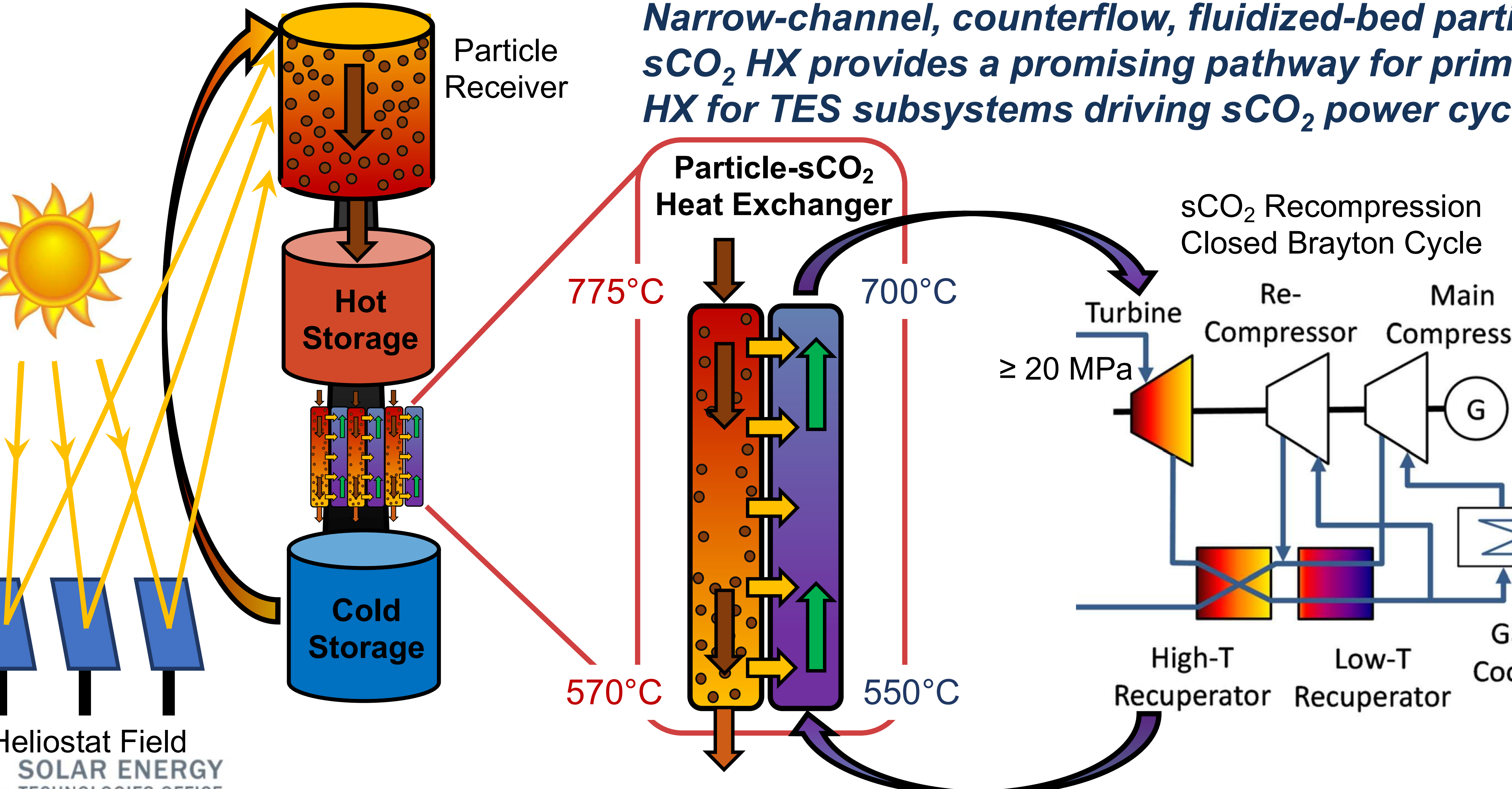
ticle-Based TES for CSP-sCO_2 Brayton Power Cycle

Narrow-channel, counterflow, fluidized-bed parti sCO_2 HX provides a promising pathway for prim HX for TES subsystems driving sCO_2 power cyc



row-channel, fluidized bed particle-sCO_2 HX design

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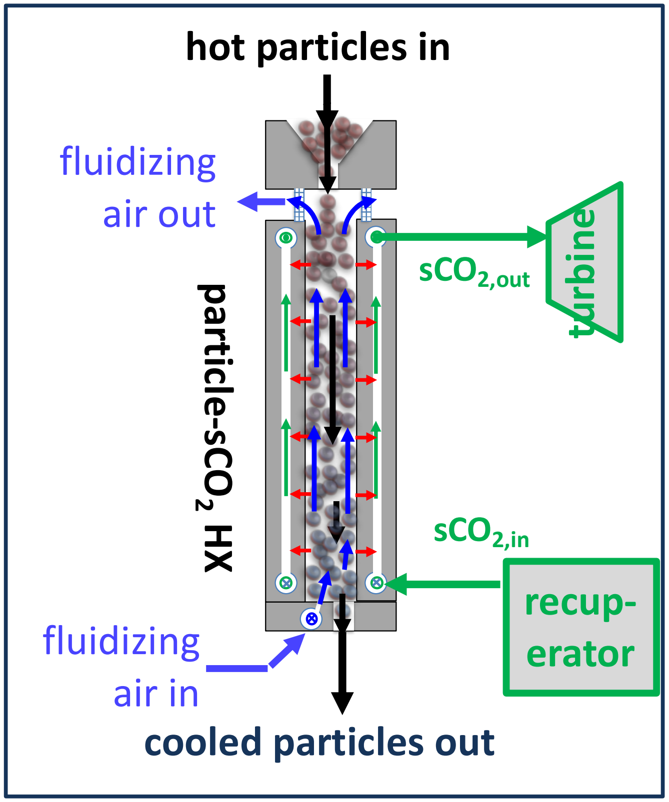
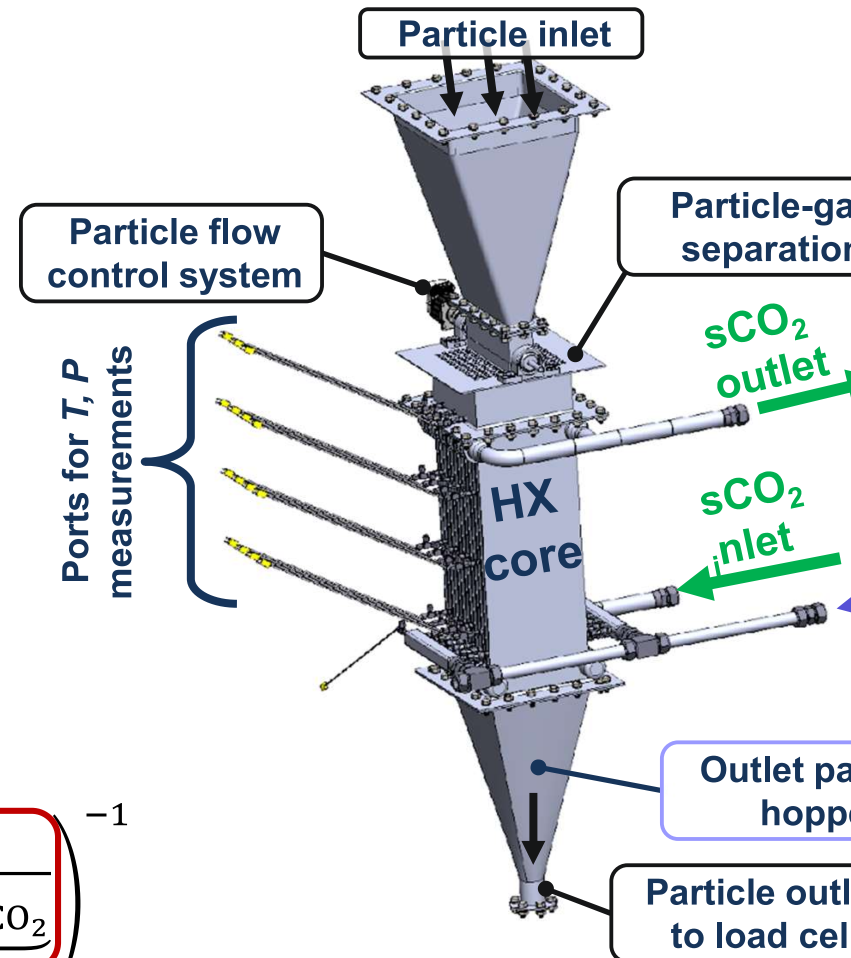
ow-channel fluidized
with mild fluidization
eve high particle-wall
associated with flux
ng thermal resistance
ive to micro-channel
$_2$ flows).

ization $\frac{\dot{m}_g}{\dot{m}_p} < 2\%$

eves optimal $h_{T,w}$.





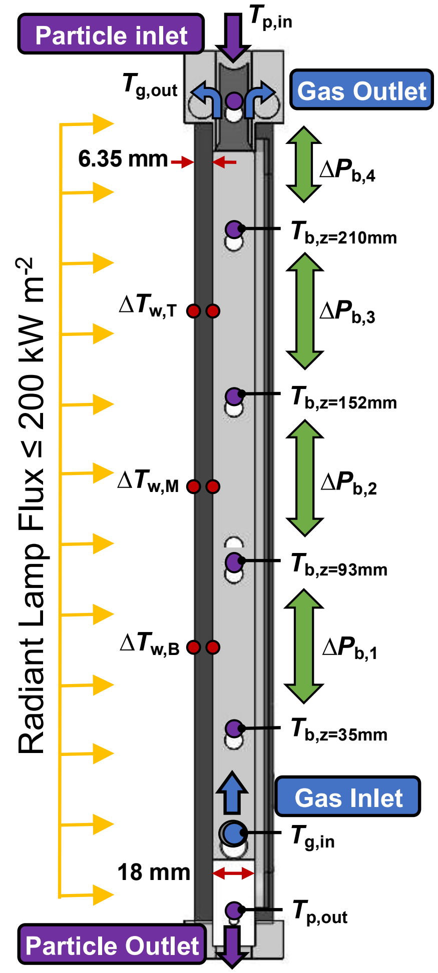
$$_2 = UA_w\left(T_p - T_{sCO2}\right)_{lm}$$

$$U = \left(\underbrace{\frac{1}{h_{T,w}}} + \underbrace{\frac{\Delta x_w}{\lambda_w}} + \underbrace{\frac{A_w}{\eta_{fin} A_{fin} h_{T,sCO_2}}}\right)^{-1}$$

Narrow-Channel Fluidized Beds:
$h_{T,w} \geq 1000\ \mathrm{W\,m^{-2}K^{-1}}$

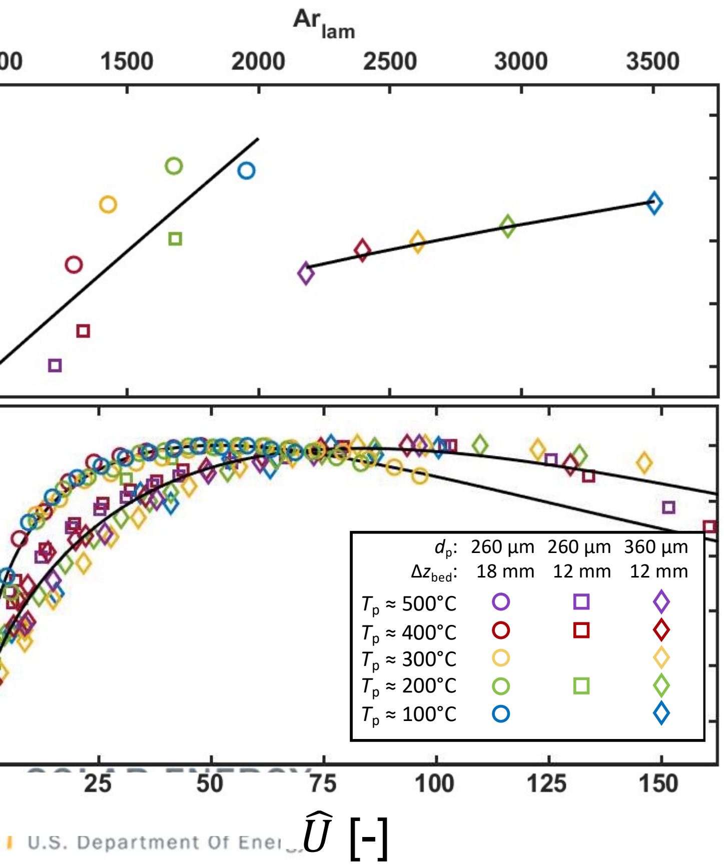
$\approx 2000\ \mathrm{W\,m^{-2}K^{-1}}$

ngle-channel Test Facility for Particle-Wall $h_{T,w}$ in Narrow-Channel Fluidized Beds



gle-channel $h_{T,w}$ Measurements and Correlations

- date, $h_{T,w}$ measurements at 6 locations in 0.25 m high bed for two channel depths (12 and), mean particle diameters (260 and 360 μm CARBO HSP), and bed temperatures up to 5
- relations based on Molerus (1992) approach with dependencies on Ar and $\hat{U}$ for convective combined with radiative contribution to provide reliable predictions of local $h_{T,w}$ in the bed.



$$h_{T,w} = h_{T,w,pc} + h_{T,w,rad}$$

$$h_{T,w,rad} = \frac{\sigma(T_b^2 + T_w^2)(T_b + T_w)}{\varepsilon_w^{-1} + \varepsilon_p^{-1} - 1}$$

Molerus (1992)

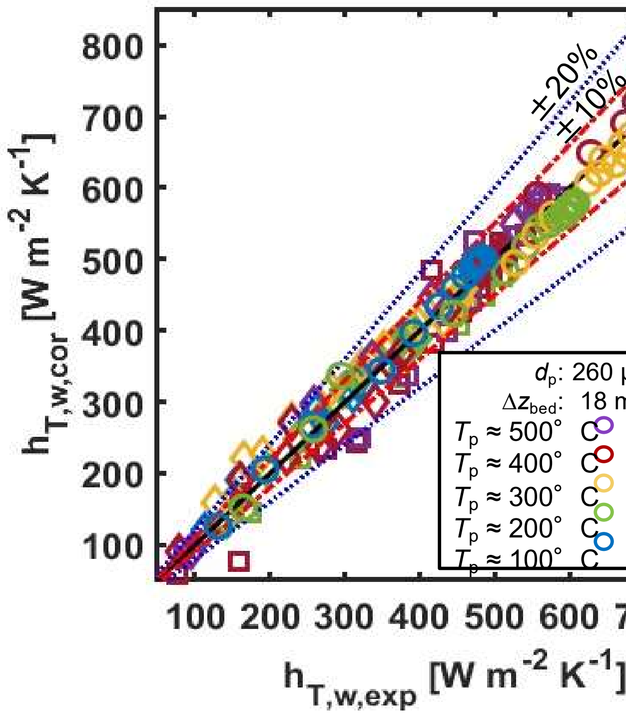
$$\mathrm{Nu}_{pc}(1 + \mathrm{Pr}_{fl}^{-1}) = f(\mathrm{Ar}_{lam}) f(\hat{U})$$

$$\mathrm{Nu}_{pc} = \frac{h_{T,w,pc}\lambda_g}{d_p}$$

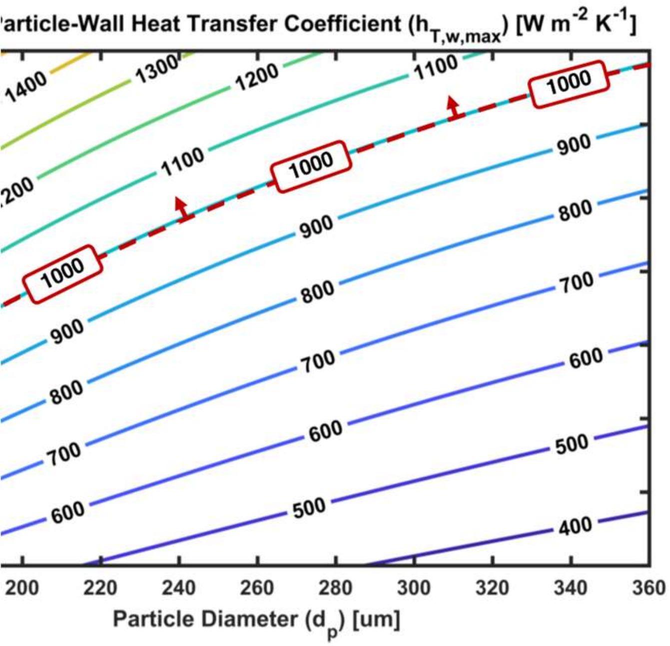
$$\hat{U} = (U_g - U_{mf})\left(\frac{\rho_p c_{p,p}}{\lambda_g g}\right)^{1/3}$$

$$\mathrm{Ar}_{lam} = \frac{\sqrt{d_p^3 g(\rho_p - \rho_g)}}{\mu_g}$$

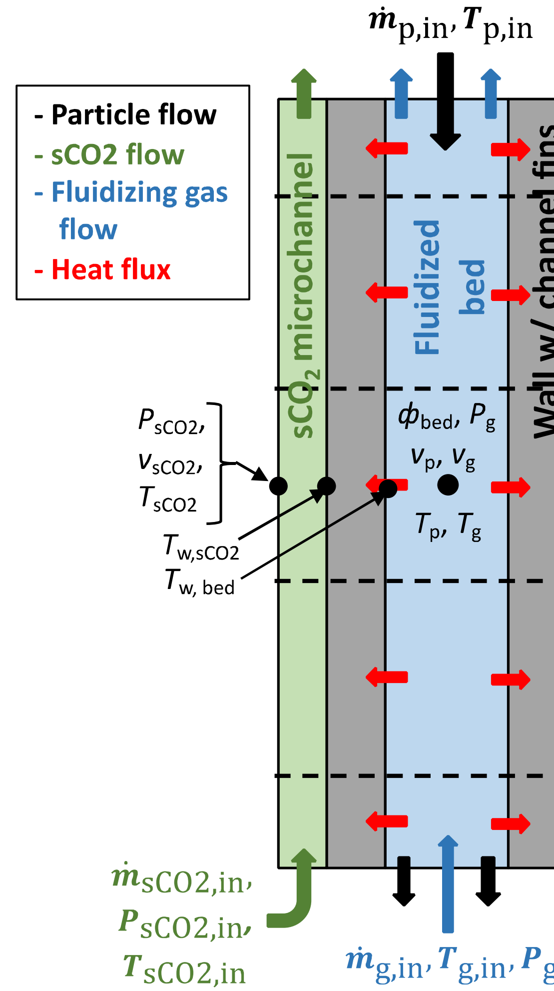
$$\mathrm{Pr}_{fl} = 2c_{p,p}\mu_g/\lambda_g$$



nverting Experimental Results into Heat Exchanger Sizes and Responses

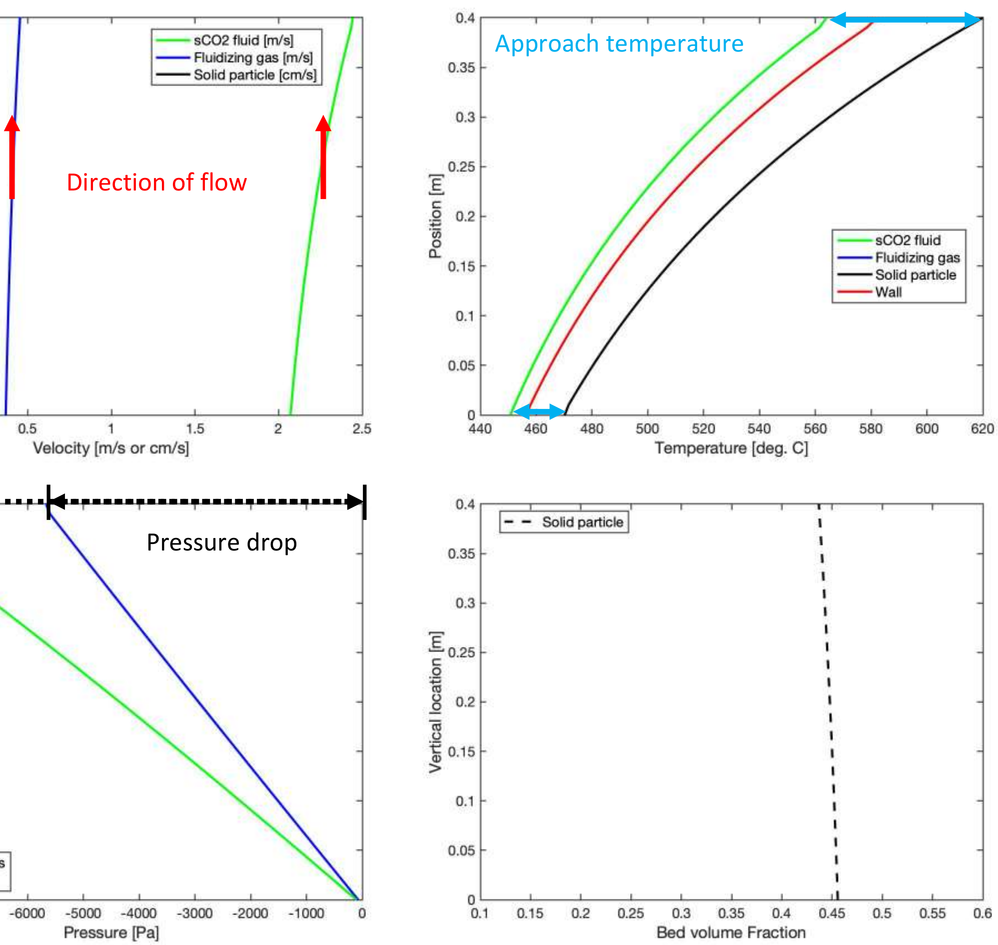


- $h_{T,w}$ correlations are integrated into vertically discretized 1-D model (MATLAB) of narrow-channel, counterflow fluidized-bed particle-sCO_2 HX to design demonstration HX geometry and assess performance at test conditions.
- The 1-D model employs a two-phase mass, momentum, and energy, fluidized bed sub-model coupled to a mass, momentum, and energy, plug-flow, microchannel sCO2 sub-model.



del-based 40-kW$_{th}$ Particle-sCO_2 HX Design

D Counterflow Fluidized Bed Model Profiles



Parameter	Baseline
$\dot{m}_{p,in,bed}$, particle flow rate per bed	18.7 g
$T_{p,in}$, particle inlet temperature	620˚C
d_p. particle diameter	260 μ
$\dot{m}_{g,in,bed}$, fluidizing air flow rate per bed	0.281 g
$T_{g,in}$, fluidizing air inlet temperature	450˚C
$\dot{m}_{sCO2,in,bed}$, sCO_2 flow rate per bed	22.4 g
$T_{sCO2,in}$, sCO_2 inlet temperature	450˚C
$\Delta y_{bed,tot}$, bed height	0.4 m
Δx_{bed}, bed width	0.2 m
Δz_{bed}, bed depth	0.015
# of beds	13
$n_{channel,bed}$, sCO_2 microchannels per bed	130
$d_{h,channel}$, sCO_2 channel hydraulic diameter	0.75 m

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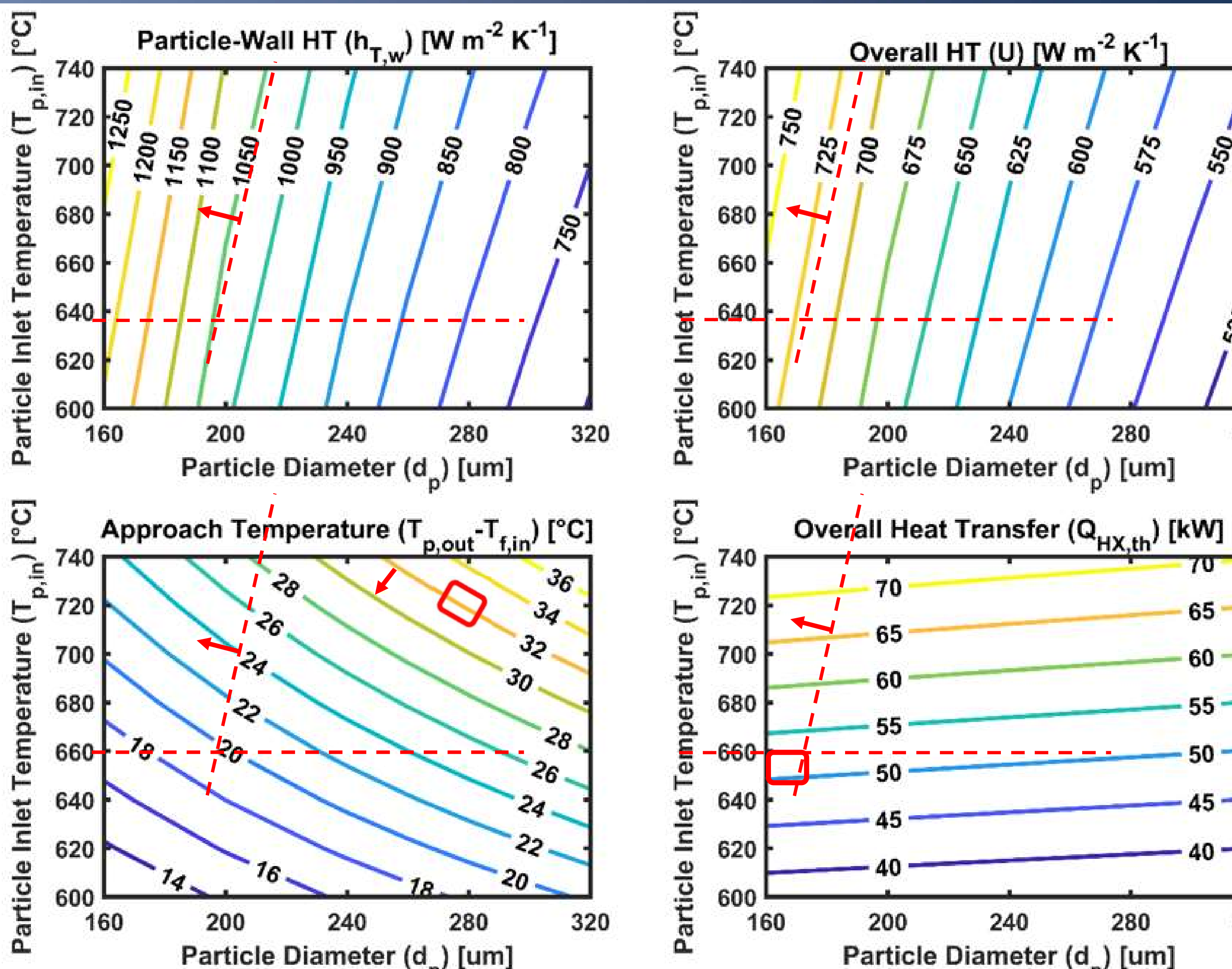
rformance of Particle-sCO_2 HX Design Space to Evaluate Costs per kW

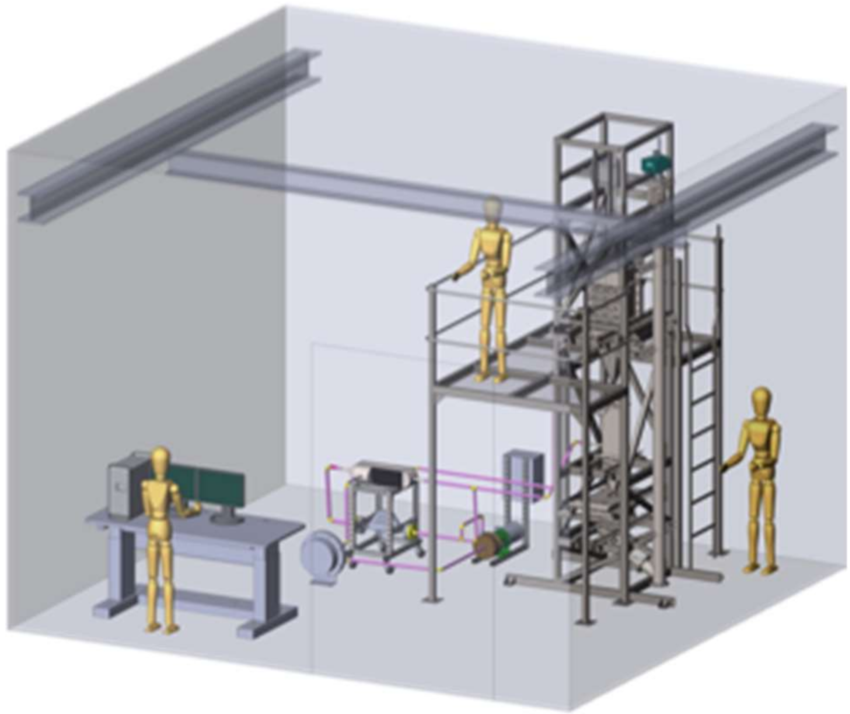
Parameter	Value
$\dot{m}_{p,in,bed}$	18.7 g s^{-1}
$\dot{m}_{g,in,bed}$	0.281 g s^{-1}
$T_{g,in}$	450˚C
$\dot{m}_{sCO2,in,bed}$	22.4 g s^{-1}
$T_{sCO2,in}$	450˚C
Δz_{bed},	0.015 m
# of beds	13
$n_{channel,bed}$	130
$D_{h,channel}$	0.75 mm



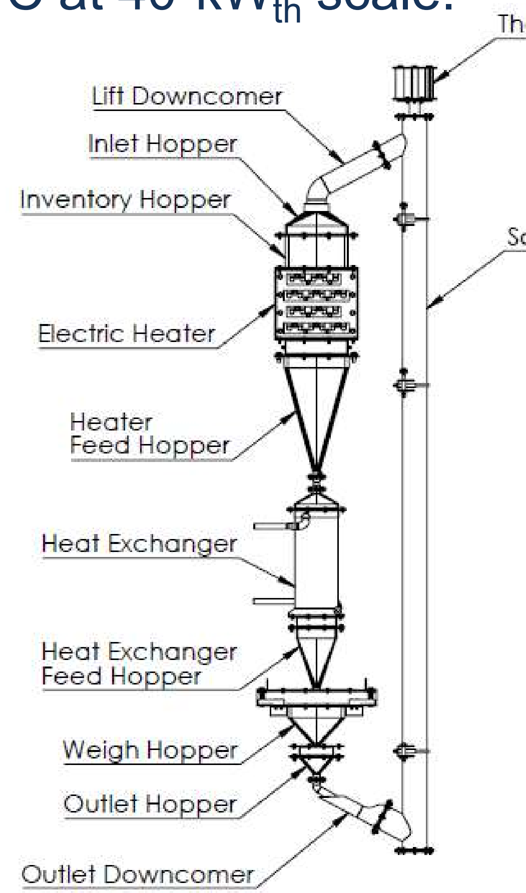
kW$_{th}$ Particle-sCO_2 HX for Test at Sandia Natl. Labs

- oration with Sandia (Kevin Albrecht and Chris Bowen) has supported the design and tion of multi-channel SS diffusion bonded 12-parallel bed HX with microchannel-sCO_2 flow
- at Sandia this fall will explore particle heat transfer at $T_{p,in}$ up to 600ºC at 40-kW$_{th}$ scale.

icated SS particle-sCO_2 HX

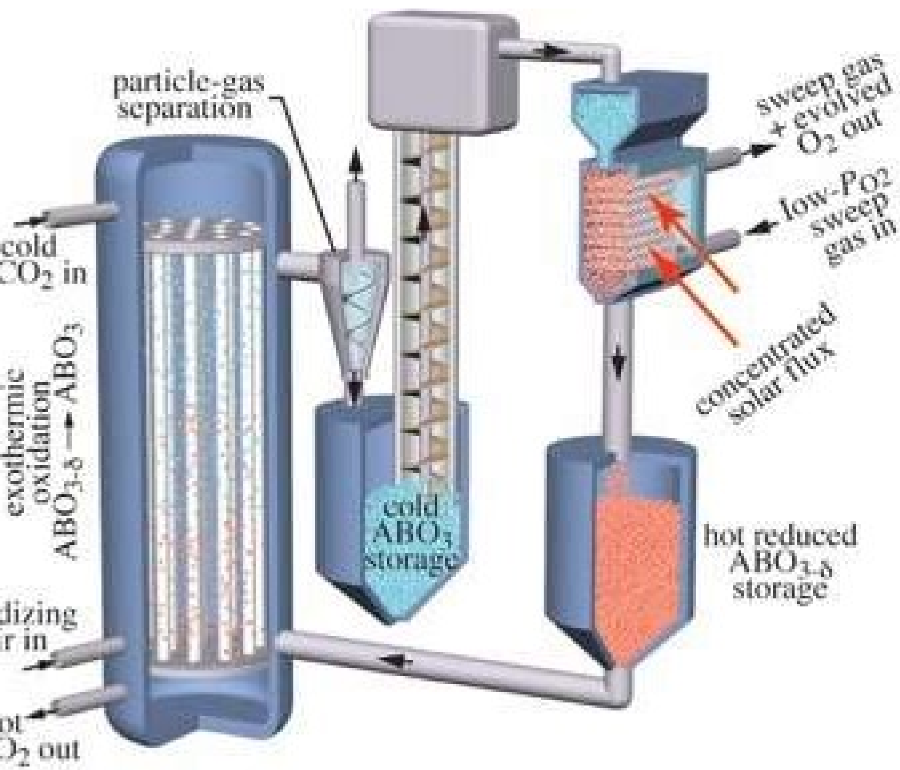


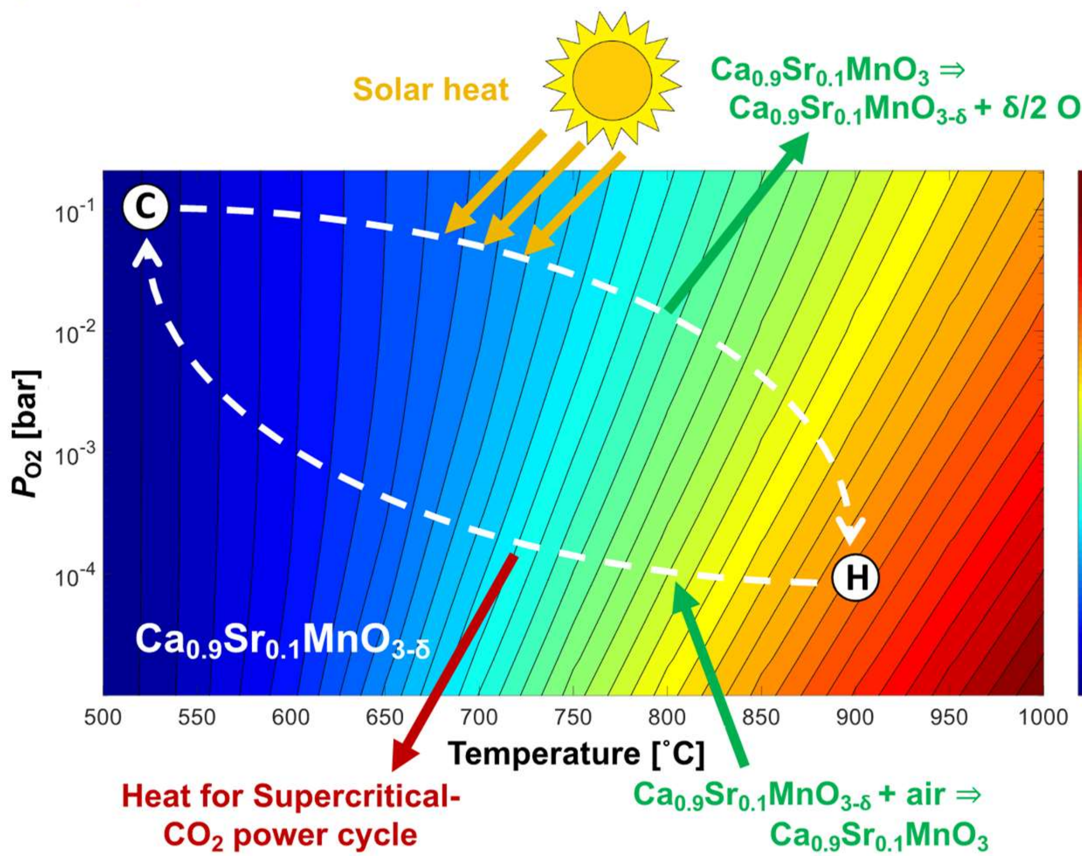
Schematic of Sandia particle-sCO_2 HX test facility



unterflow Fluidized Beds Can Support Thermochemical Energy Storage (TCES) for CSP

mpleted Mines-led CSP-ELEMENTS program with NREL collaboration
plored fluidized bed design for redox active perovskites (doped $CaMnO_{3-\delta}$) t
re than double energy storage density of particles.





ncluding Remarks and Path Forward

w correlation developed from single channel rig for narrow-channel fluidized ds to include new data obtained at 100–500ºC with 260 and 360 μm particl 12 & 18 mm deep beds for a range of gas-to-particle mass flow ratios.

D discretized models using $h_{T,w}$ correlation enabled assessment of geometr rameters and operating conditions to design a 40-kW$_{th}$ prototype HX fabrica VPE for testing at Sandia National Labs this fall.

verage $h_{T,w} \approx 700$ W m^{-2} K^{-1}, overall $U \approx 500$ W m^{-2} K^{-1}, $\epsilon_{HX} \approx 0.80$, $q''_{w,avg} \approx 24$ kW m^{-2} redicted with CARBOBEAD HSP40/70 at planned test conditions.

eat transfer models can be utilized for scale-up and for exploring more comp stem designs for other applications such as thermochemical energy storage