Modeling and Optimization of a Multiple Tube Receiver for High Temperature Solar-Thermal Processes

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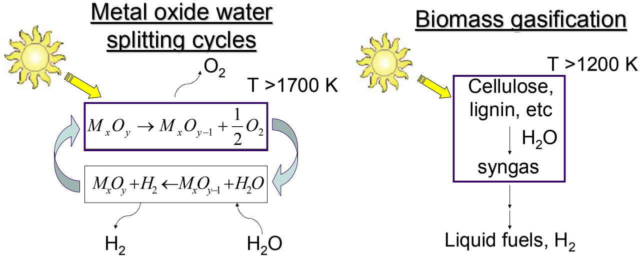
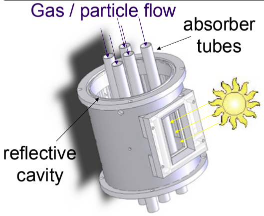
Solar-Thermal Processes



Concentrated solar energy is used to attain high temperatures and carry out strongly endothermic chemical reactions to transform renewable feedstocks into usable fuels

Receiver Design



- Reflective aluminum cavity with quartz window encloses 5 flow tubes
- Cooling zones surround front, back, top, bottom and window

Radiation Models

Hybrid Monte Carlo (MC) / Finite Volume (FV) radiation model

- Solar radiation in the receiver cavity → Monte Carlo
- Emitted radiation in the tubes and cavity → Finite volume

$$\frac{di_\lambda'}{ds} = -(a_\lambda + \sigma_{s\lambda})i_\lambda'(s) + a_\lambda i_{\lambda b}'(\lambda, T) + \frac{\sigma_{s\lambda}}{4\pi}\int_0^{4\pi} i_\lambda'(s,\omega_i)\phi(\lambda,\omega,\omega_i)d\omega_i$$

Particle absorption efficiency, scattering efficiency, and scattering phase function from Mie theory

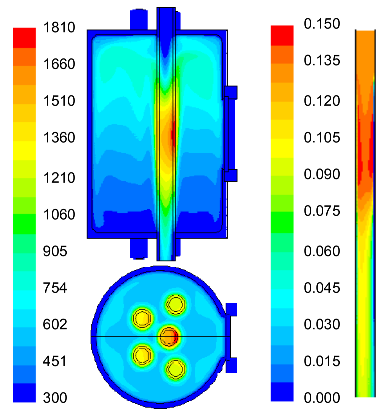
Fluid flow and reaction models

- 3D steady state solutions to the heat, mass, momentum, and species transport equations
- Gasification of 40 nm acetylene black particles

$$C_{(s)} + H_2O_{(g)} \rightarrow CO_{(g)} + H_{2(g)} \qquad \Delta H_r^0 = 131.3 \text{ kJ/mol}$$

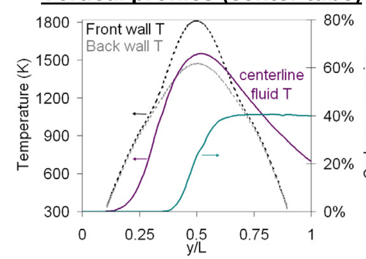
- Laminar flow (Re<250, Gr<10^6), ideal gases, particles entrained in fluid (St<10^{-5}), mixture properties = $f(T,y_i)$
- Thermophoretic diffusion of solids
- Progressive conversion particle reaction model (η > 0.99)
- Homogenous water-gas shift reaction

Model Results



- 0.5 g/min C per tube, 2x stoich. H_2O, 1SLPM Ar
- 6kW solar power, flux profile at window surface from ray-trace models of HFSF

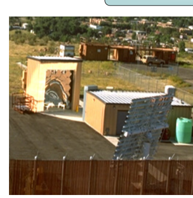
Vertical profiles (center tube)

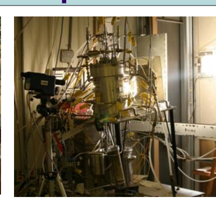


	Solar energy absorbed (kW)	Max T (K)	Carbon conversion
Center tube	1.97	1790	40.2%
Front tube	0.47	1333	2.5%
Back tube	0.99	1522	9.2%

- Large gradients across tube surfaces
- Non-uniform heating
- Small heated length
- Low efficiency (~2%)

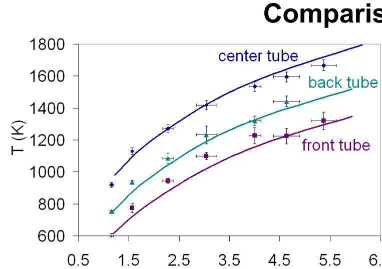
Experimental validation

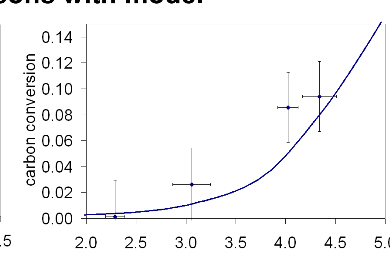




- Experiments carried out on-sun at NREL's High Flux Solar Furnace
- SiC or Inconel 600 tubes
- 0.4 mg/s C (center tube), 3x stoich. H_2O, 1SLPM Ar

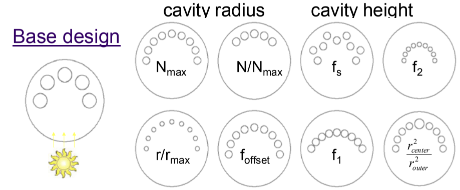
Comparisons with model





Optimization

- Reflective and absorbing cavity configurations
- Series of resolution IV fractional factorial designs, 14 factors
- Face-centered central composite design, 5 factors



Operating conditions
Solar power
C feed rate
Steam / C ratio
Ar flow

Response
efficiency

Significant effects

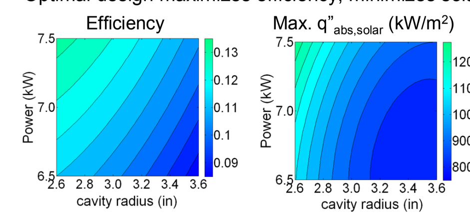
Significant	Insignificant
Cavity radius Solar power C feed rate N_{max}, N/N_{max} tube radius	f_{offset} f_1 f_s cavity height

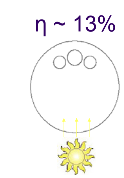
Features of best designs

Reflective (cooled)	Absorbing (insulated)
Allow energy to reflect off cavity wall	Minimize energy incident on cavity wall
Intermediate tube radius	Largest possible tube radius
3 tubes placed within solar beam	3 - 5 tubes, can be outside of solar beam

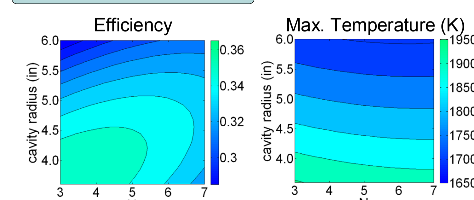
Reflective cavity

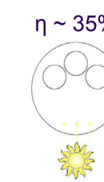
- Optimal design maximizes efficiency, minimizes solar flux, temperature





Absorbing cavity





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