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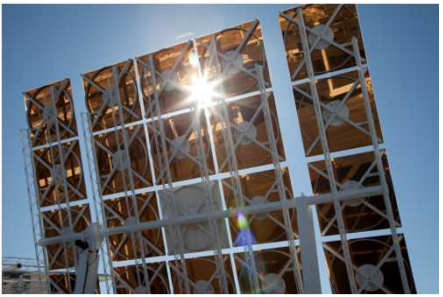


Fractal-Like (Volumetric) Particle Receiver Designs

SuNLaMP Project – 18 months

Lead: Sandia National Laboratories

Partner: Abengoa Solar

PI: Cliff Ho, SNL

SAND2015-XXXX

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

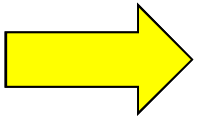
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Objective

- Develop new particle release configurations that increase solar absorptance and thermal efficiency

Need Receivers for Higher Temperature Applications

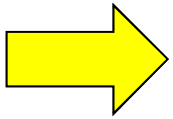
- Electricity production
  - Supercritical CO_2 Brayton Cycles (>700 C)
  - Air Brayton Cycles (>1000 C)
    - Combined cycles
    - APOLLO/AETHER
- Thermochemical
  - ELEMENTS/PROMOTES project (>1000 C)
  - Solar fuel production (>1000 C)



Particle Receivers

Particle Receivers - Challenges

- Indirect particle heating
  - Hot spots and flux limitations on particle containing surfaces
  - Heat transfer limitations from walls to particles
  - Significant re-radiation losses from walls at high temperatures
- Direct particle heating
  - Free-falling linear curtains may not be able to achieve sufficient temperatures
  - Obstructed flow systems still need to be proven at high irradiance and T > 1000 C
  - May need particle recirculation to get to higher temperatures >1000 C

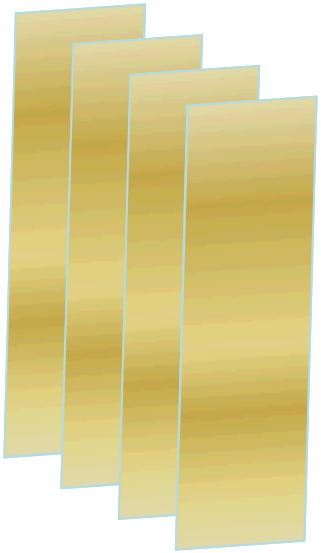


Employ fractal-like (volumetric) particle receiver designs to increase efficiency at higher particle temperatures

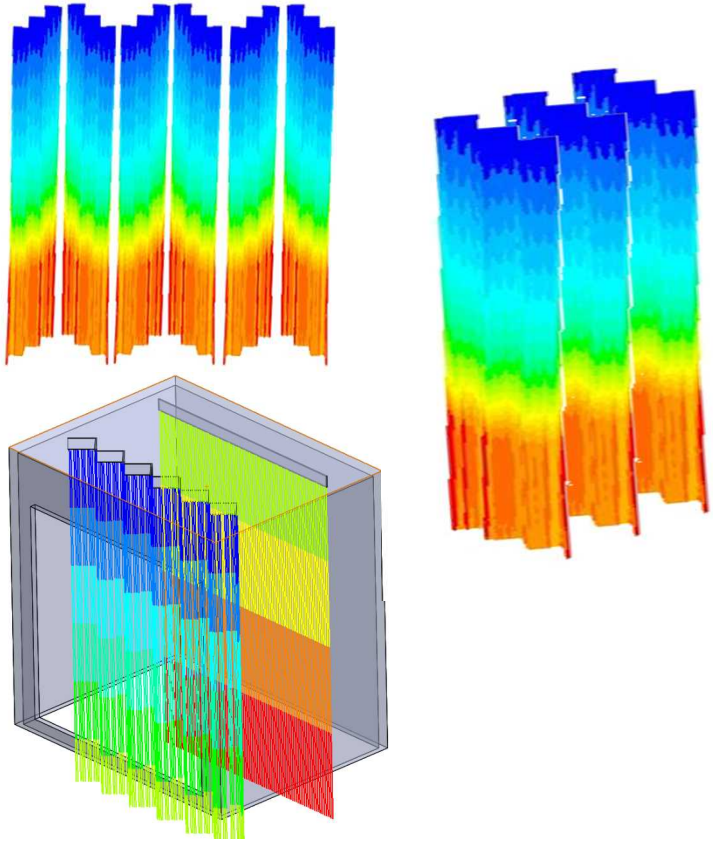
Approach – Particle Receivers

- Develop fractal-like (volumetric) particle flow configurations across multiple scales to increase solar absorptance while minimizing heat loss

Conventional linear particle curtain



Abengoa Solar Proprietary (AETHER/APOLLO Proposal)



Sandia provisional patent U.S. 62/145136

Evaluation of Flat vs. Wavy (Volumetric) Particle Curtain Configurations

Alternative Particle Release Patterns

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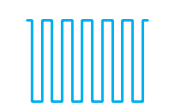
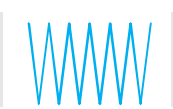
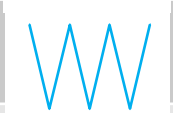
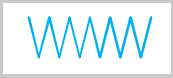
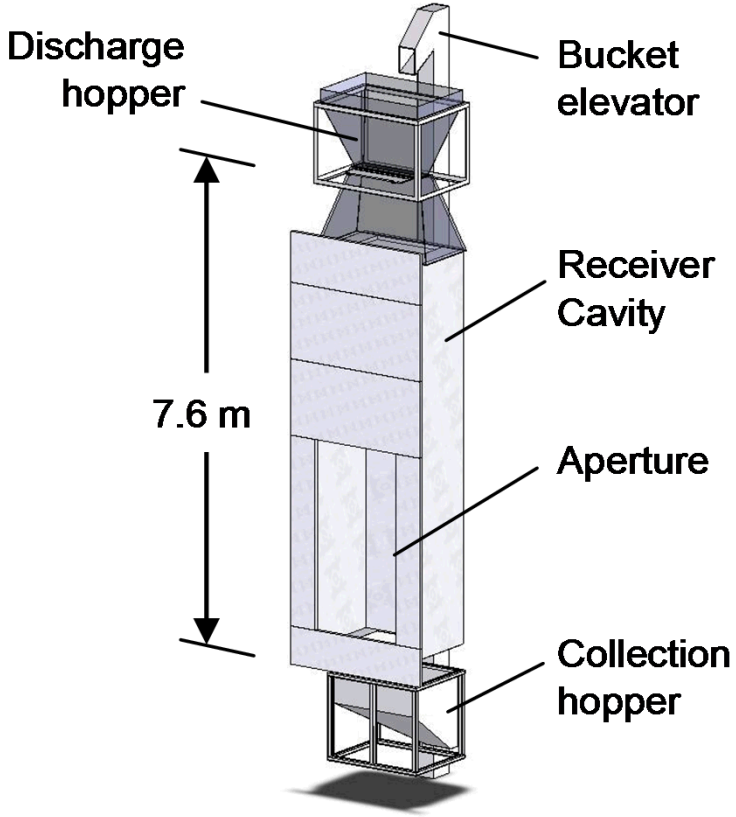
Case	Amplitude (m)	Wavelength (m)	Wave Form	Illustration
Baseline	N/A	N/A	N/A	
Case 1	High (0.4)	High (0.33)	Square	
Case 2	High (0.4)	Low (0.17)	Square	
Case 3	High (0.4)	Low (0.17)	Triangle	
Case 4	High (0.4)	High (0.33)	Triangle	
Case 5	Low (0.2)	High (0.33)	Square	
Case 6	Low (0.2)	Low (0.17)	Triangle	
Case 7	Low (0.2)	High (0.33)	Triangle	
Case 8	Low (0.2)	Low (0.17)	Square	

On-Sun Tests

(Siegel and Kolb, 2008)

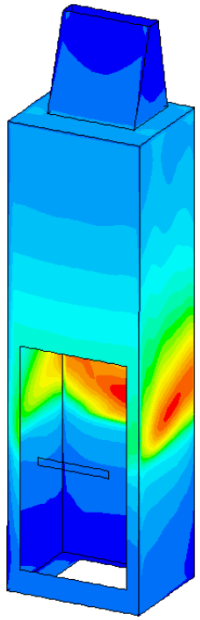
- Nine on-sun tests performed with varying particle mass flow rates (3.8 – 8.7 kg/s-m) and total concentrated thermal input power (1.6 – 2.5 MW_{th})



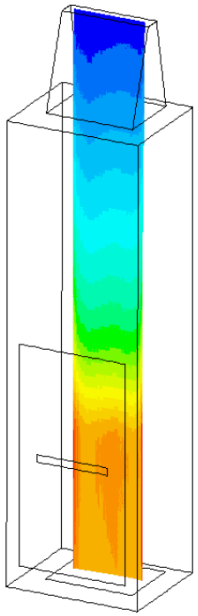
Computational Model Validated

Ho et al. (2009)

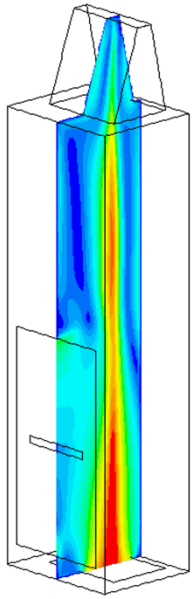
- 3-D model in FLUENT
  - Irradiation from heliostat field
  - Two-band reradiation and emission within cavity
  - Discrete-phase particle transport and heat transfer
  - Gas-phase convection and interaction with particles
  - Wall conduction
  - Radiative and convective heat losses



Incident radiation on walls

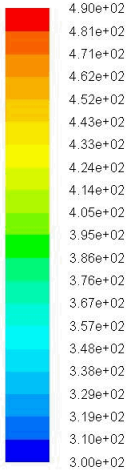


Particle tracks colored by temperature

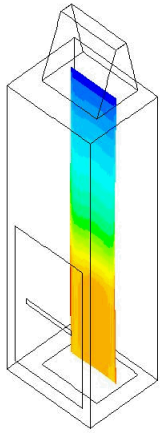


Gas flow colored by velocity

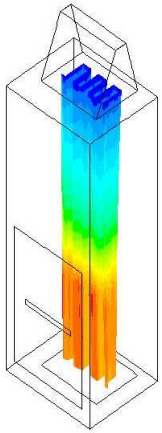
Results – Particle Temperatures



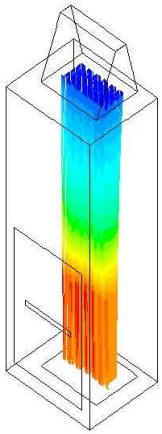
Baseline



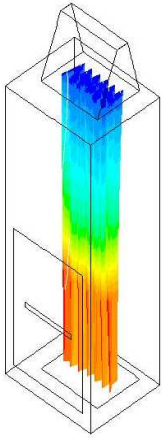
Case 1



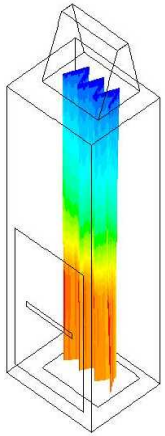
Case 2



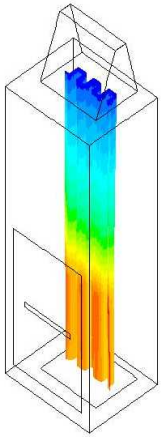
Case 3



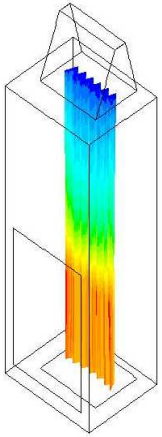
Case 4



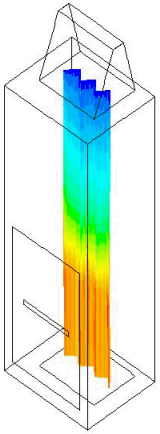
Case 5



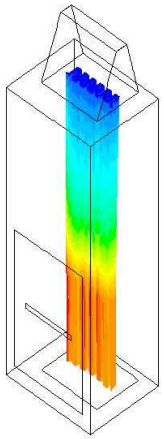
Case 6



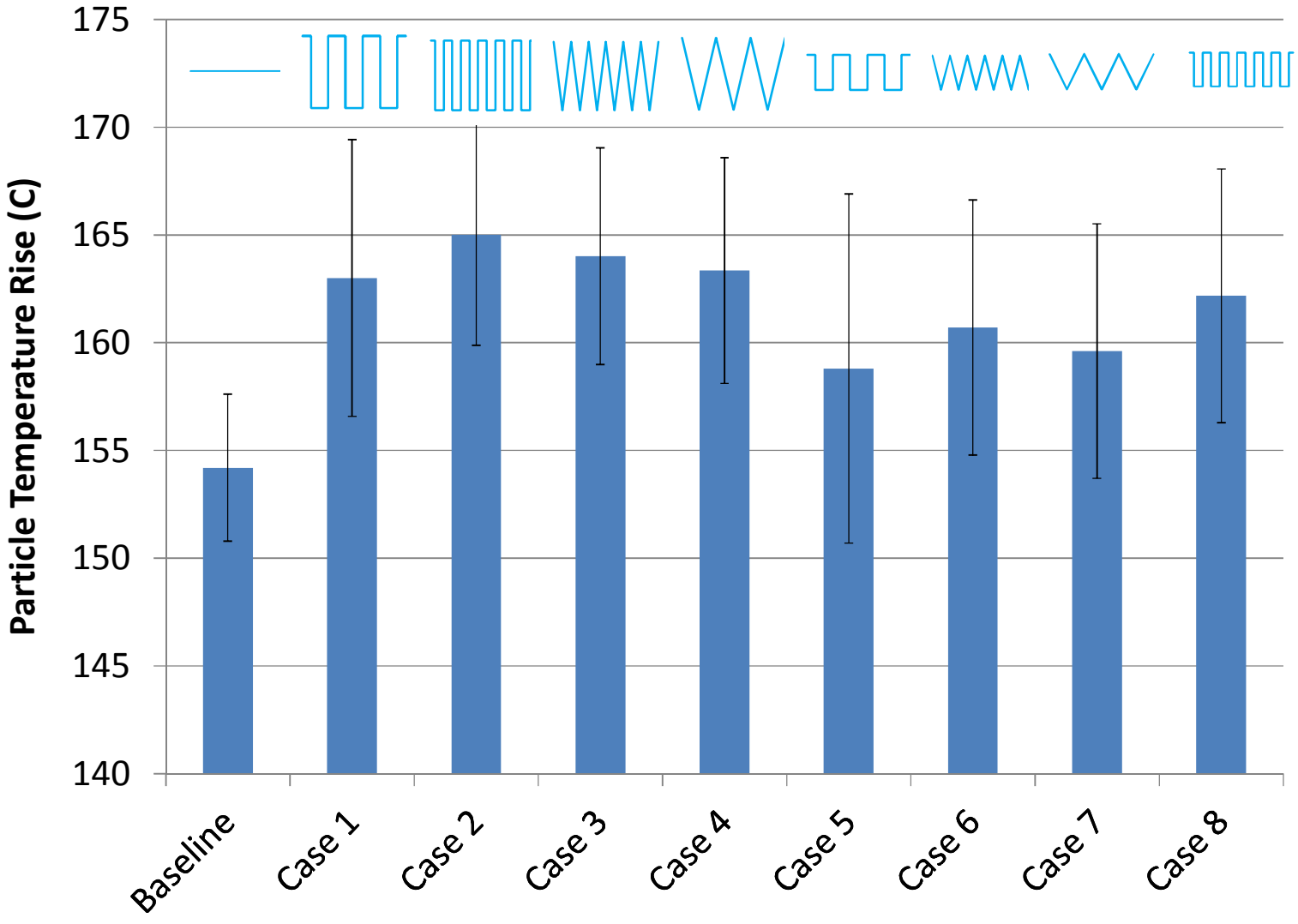
Case 7



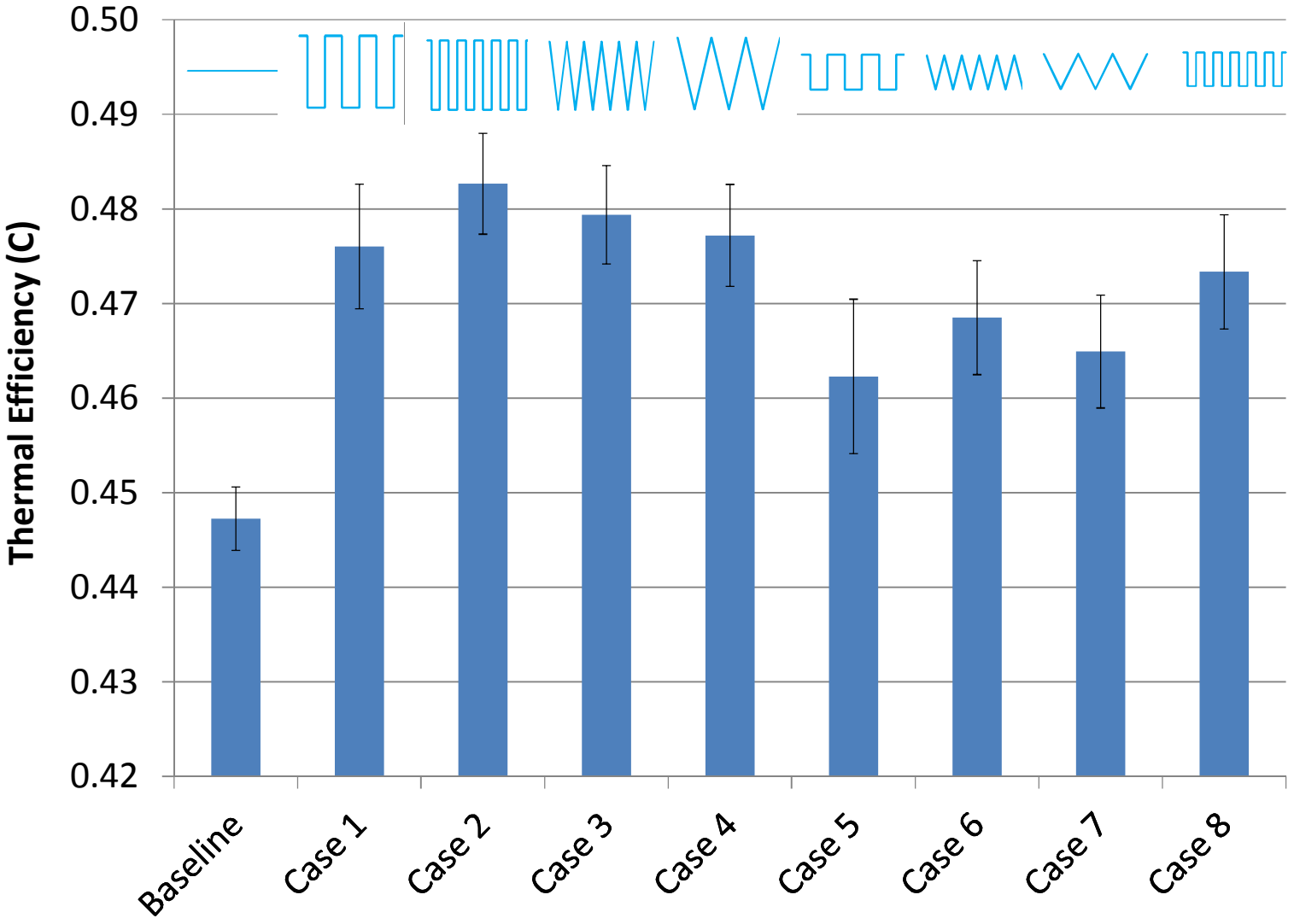
Case 8



Results – Particle Temperatures



Results – Thermal Efficiency



ANOVA Sensitivity Analysis

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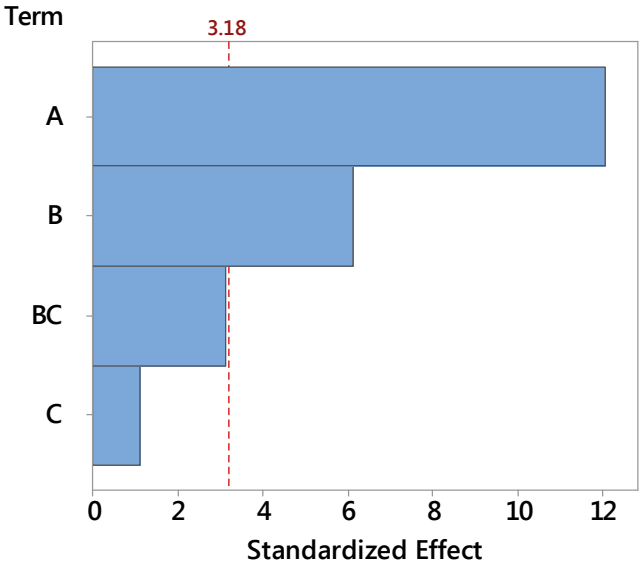
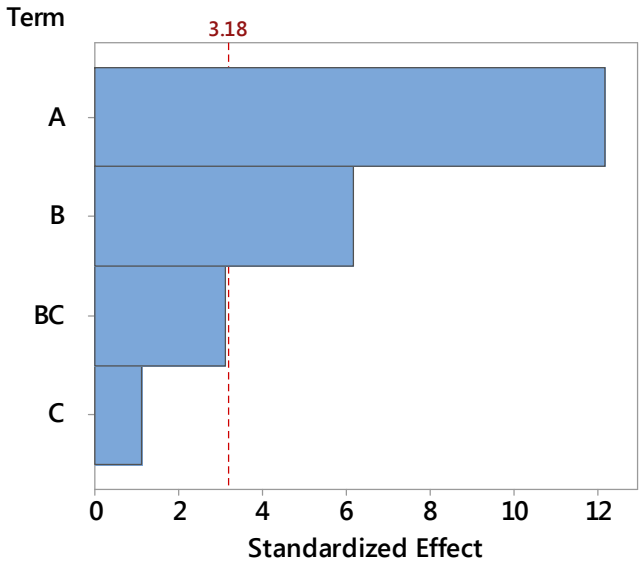
Particle Temperature Rise



Factor	Name
A	Amplitude
B	Wavelength
C	Wave Form

Thermal Efficiency



Factor	Name
A	Amplitude
B	Wavelength
C	Wave Form

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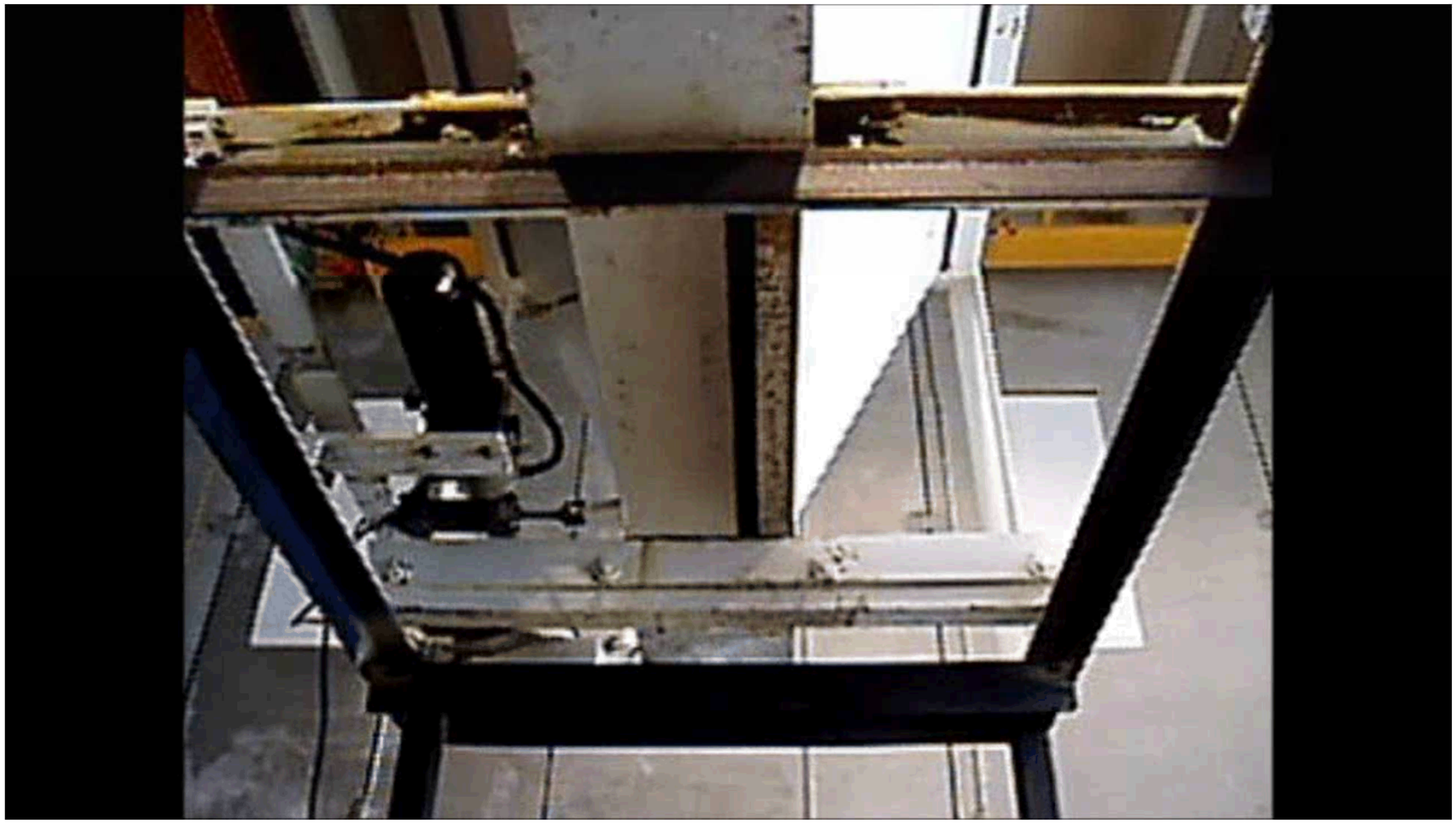
Testing

Linear Release



Zig-Zag Release

Impact

- Fractal-like / volumetric particle receiver curtains/geometries
  - Increase effective solar absorptance (light trapping)
  - Reduce local thermal emittance in hottest regions
    - Provide insulation with particles falling near aperture
  - Control transmittance through particle curtains
  - Enable higher temperatures while minimizing heat losses
- Coupled optical/thermal/fluid models developed
  - Simulated effective solar absorptance and thermal efficiency increased >5% with fractal-like geometries
    - Zig-zag particle curtain yielded higher particle temperatures and efficiencies than flat curtain
- Volumetric particle receiver designs will enable new high-temperature designs and applications (> 1000 C)

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Backup Slides

Why Volumetric Particle Receivers?

- Volumetric receivers in theory can achieve very high efficiency by heating the media in the interior portions
  - Increase solar radiation capture and minimize losses
- This has not be realized because the hottest regions are near the aperture in practice (PSA, Julich)
- Volumetric Particle Receivers have an advantage
  - We can design particle curtain configurations to control the transmittance to interior regions of the receiver

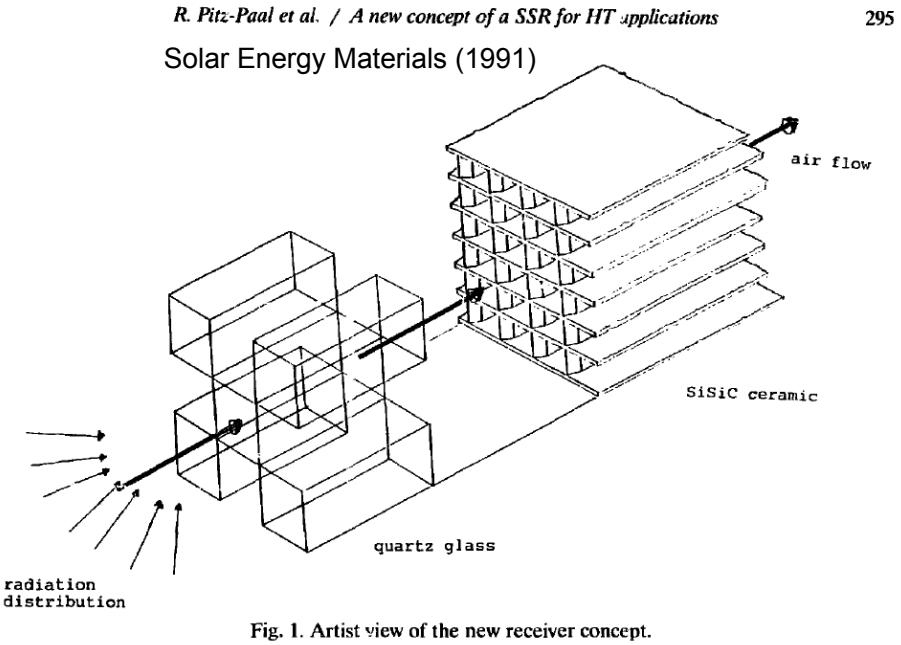
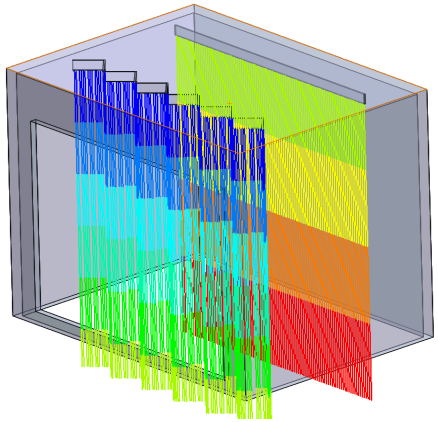
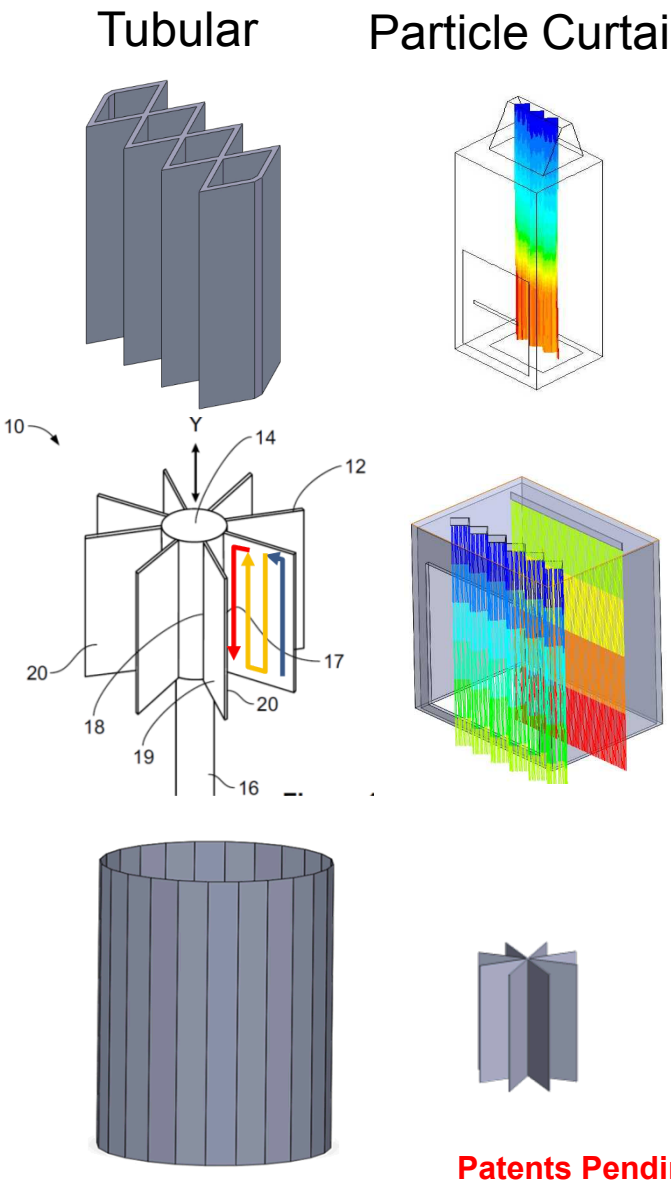


Fig. 1. Artist view of the new receiver concept.



Hypotheses

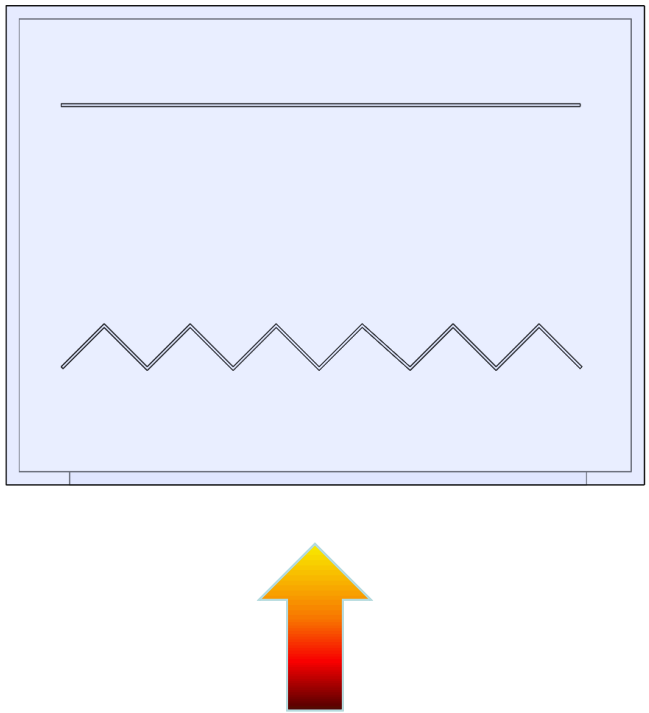
1. Increase light trapping and effective solar absorptance
2. Reduce thermal emittance by reducing local view factors in hottest regions
3. Increase thermal efficiency and reduce heat loss by increasing concentration ratio and reducing overall aperture size (optical intercept) of receiver while maintaining the same exposed surface area and irradiance

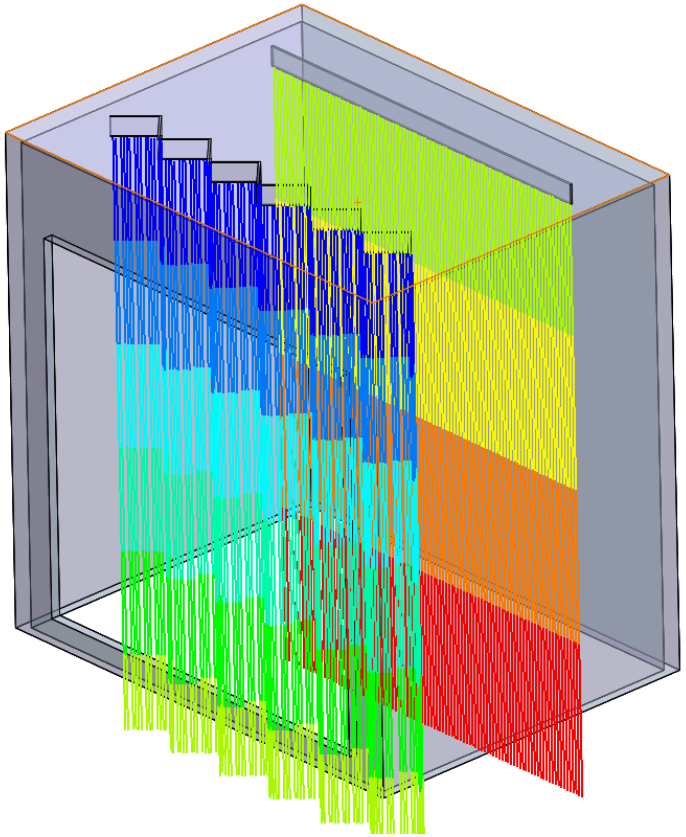


Patents Pending

Fractal-Like Particle Curtains

- Create volumetric effect





provisional patent U.S. 62/145136

Unheated Results

Ho et al. (2009)

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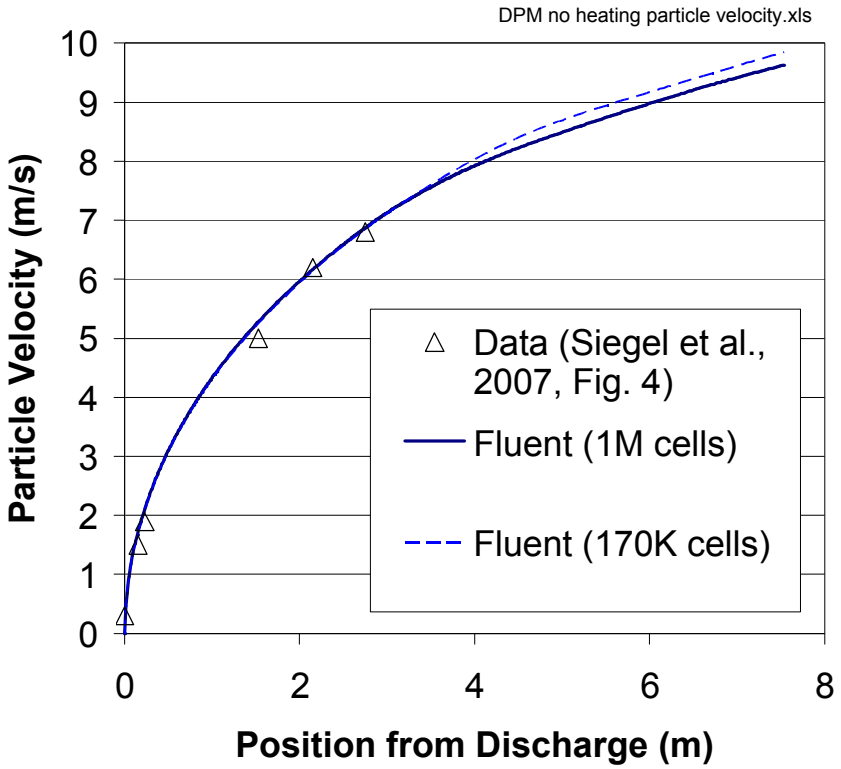
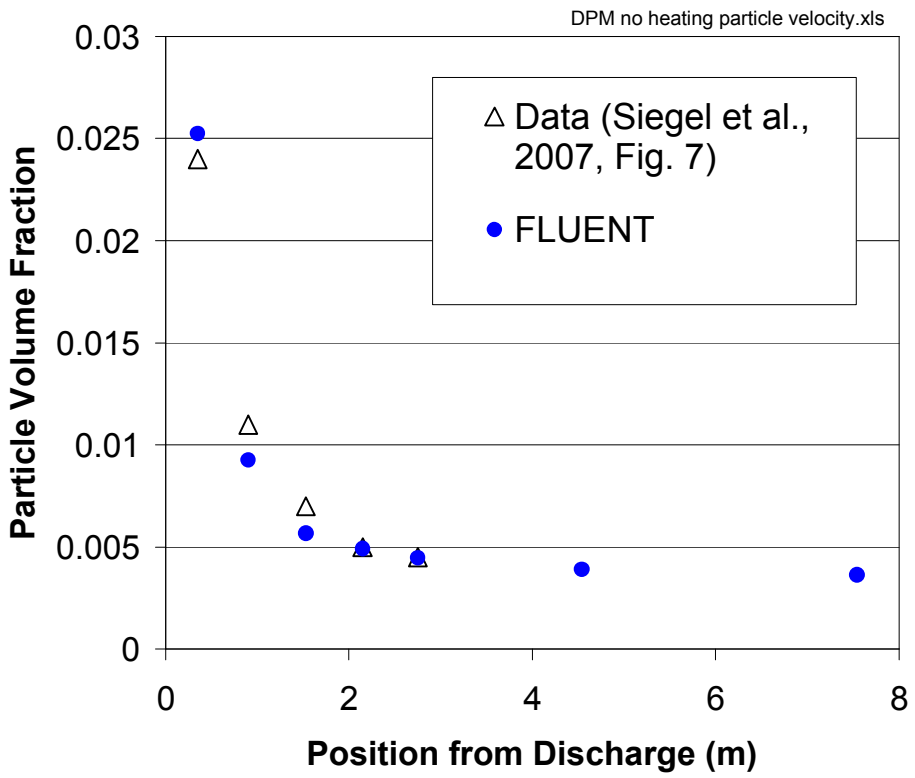
Particle Velocity

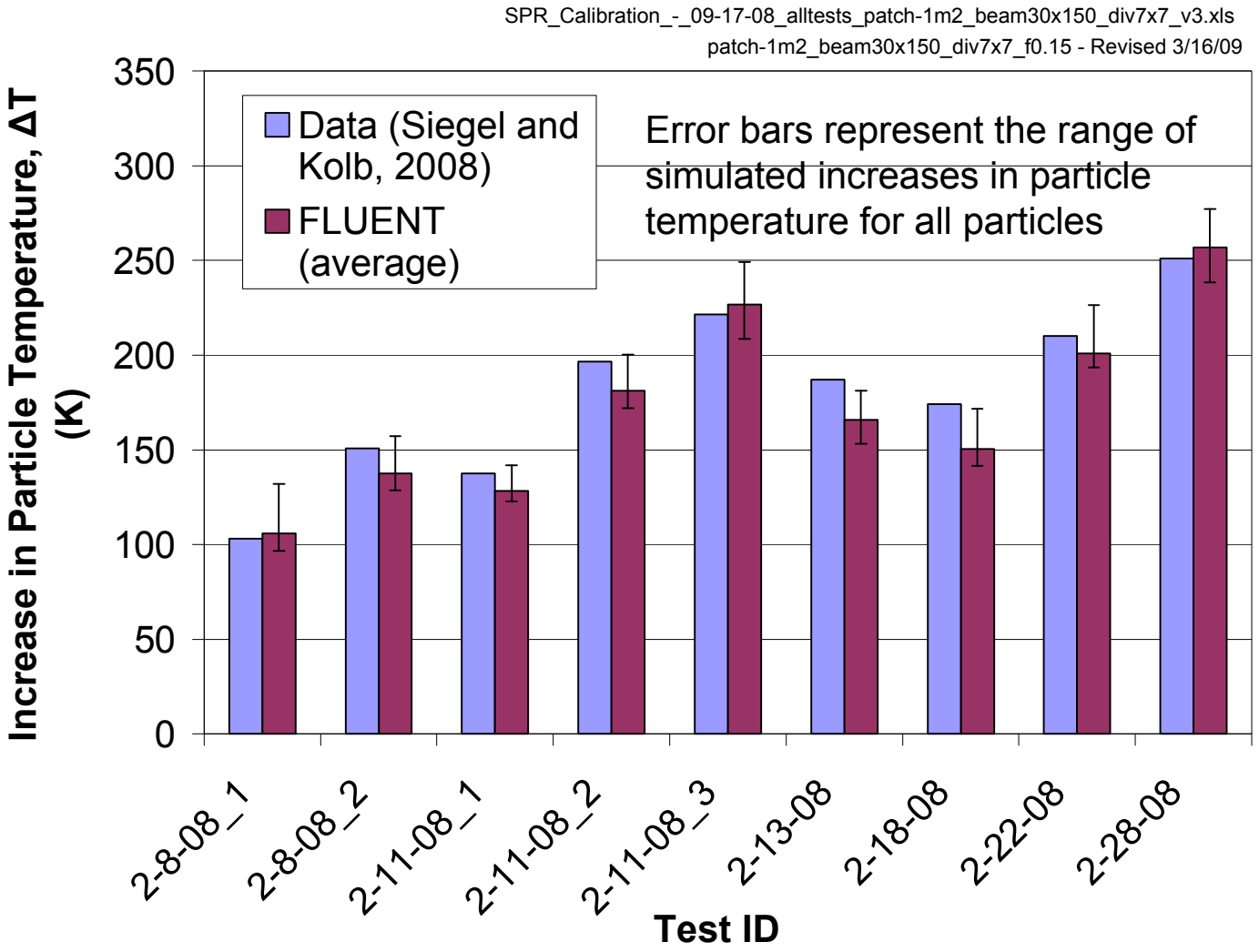


Particle Volume Fraction



Particle Temperature Increase

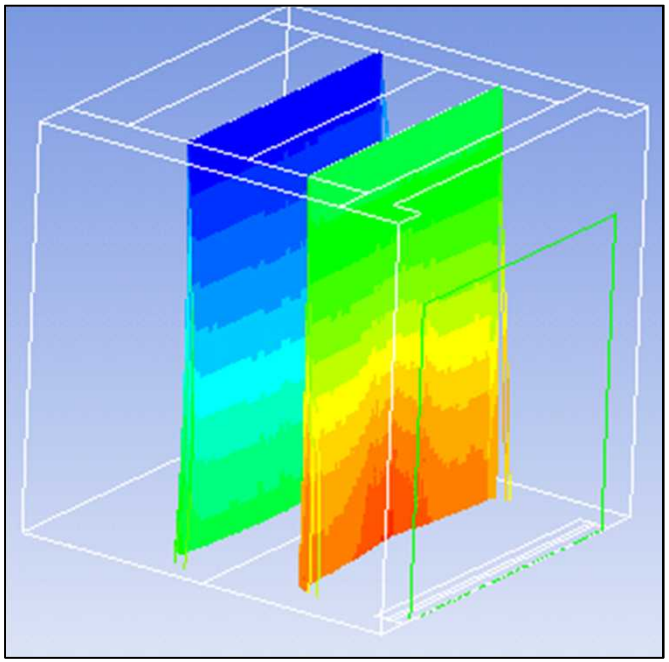
Ho et al. (2009)

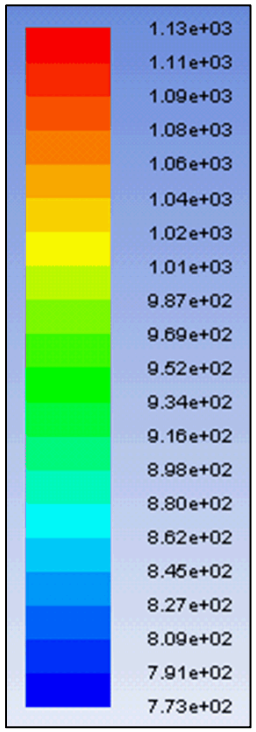


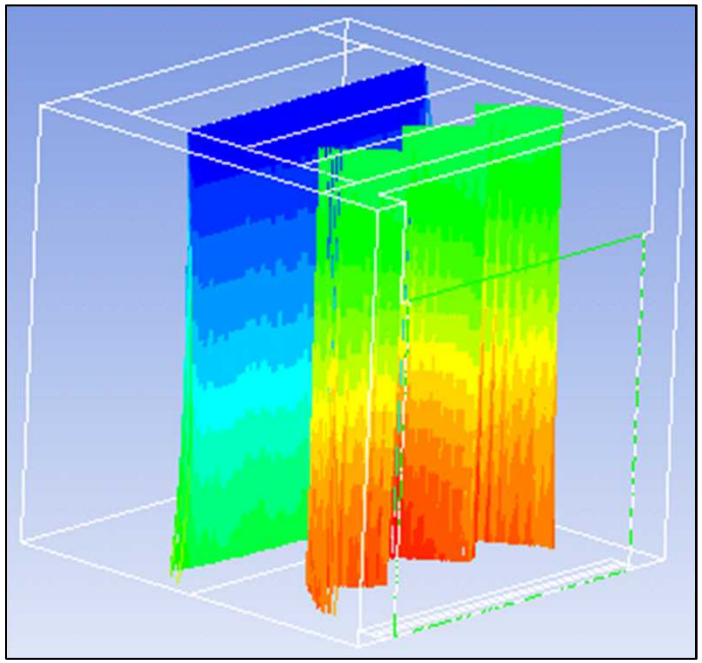
Evaluation of Volumetric Particle Receiver Designs with Recirculation

Results – Back-to-Front Recirculation

- Linear Drop Pattern
  - η = **74.6%**
  - First drop particle outlet temperature = **654° C**
  - Final drop particle outlet temperature = **803° C**
- Zig-Zag Drop Pattern
  - η = **75.5%**
  - First drop particle outlet temperature = **652° C**
  - Final drop particle outlet temperature = **807° C**







Results – Front-to-Back Recirculation

- Linear Drop Pattern
  - η = **76.2%**
  - First drop particle outlet temperature = **686° C**
  - Final drop particle outlet temperature = **809° C**
- Zig-Zag Drop Pattern
  - η = **77.0%**
  - First drop particle outlet temperature = **696° C**
  - Final drop particle outlet temperature = **813° C**