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Pairing Directional Solar Inputs from Ray Tracing to Solar Receiver/Reactor Heat Transfer Models on Unstructured Meshes: Development and Case Studies

H. Evan Bush, Andrew J. Schrader, Peter G. Loutzenhiser

Georgia Institute of Technology

The American Society of Mechanical Engineers® ASME®

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- Case Studies

Introduction

Motivations

- Concentrated solar inputs are highly directional and often spatial
- Modeling concentrator, receiver simultaneously may be impractical
- Conversion from the concentrator radiation model (ray tracing) to receiver physics model (CFD) is a potential source of error
- Some existing methods are cumbersome, imprecise, or inaccurate

Ray-Trace + CFD Pairing Schemes

Non-overlapping Domains

- Concentrator and receiver paired at shared external boundary
- Use: participating media (fluidized particles)
- May require high mesh, boundary condition resolution

Overlapping Domains

- Pairing at shared internal receiver boundary/volume
- Use: "one way" or radiatively decoupled collector and receiver
- May allow coarser mesh, but can impose significant errors

Ray-Trace + CFD Pairing Schemes

Non-overlapping Domains

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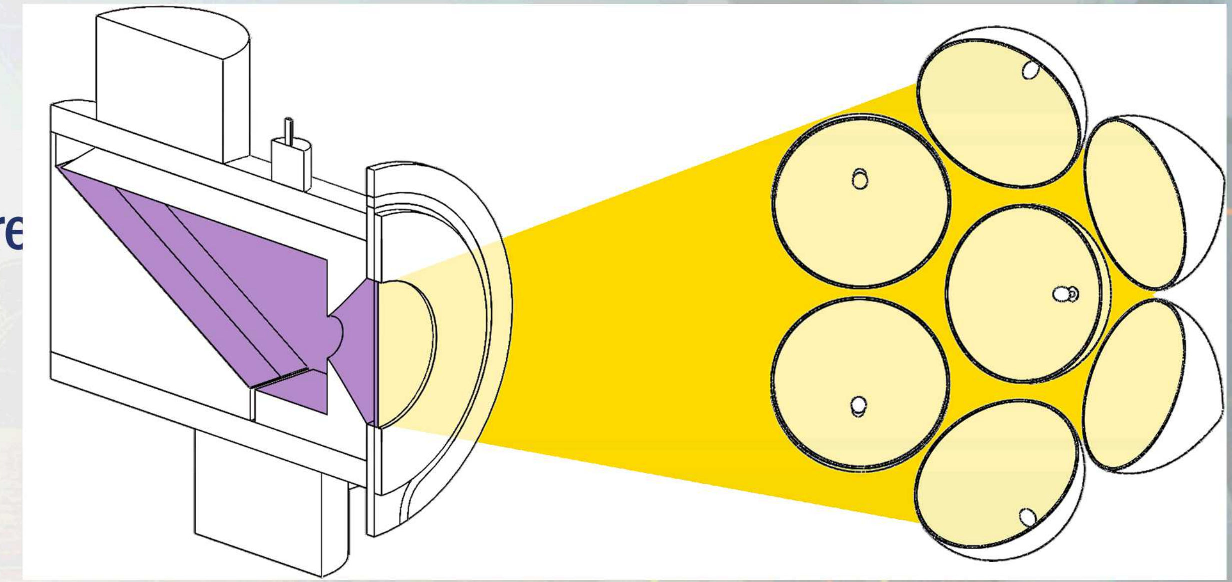
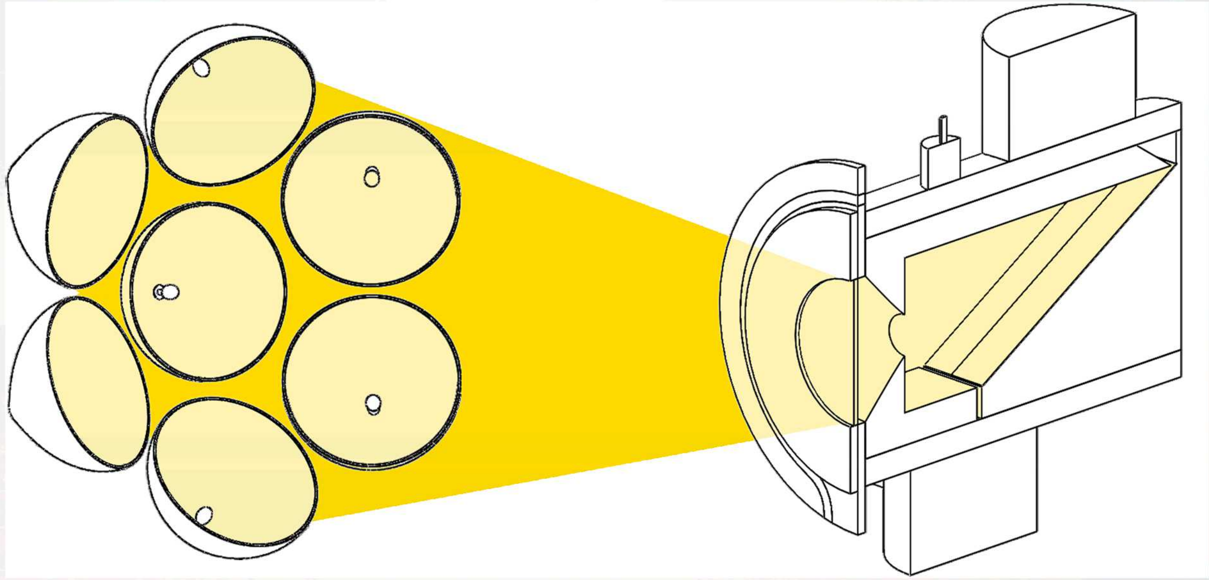


CFD (ANSYS Fluent)   Monte Carlo Ray Tracing

Ray-Trace + CFD Pairing Schemes



Monte Carlo Ray Tracing

CFD (ANSYS Fluent)

Overlapping Domains

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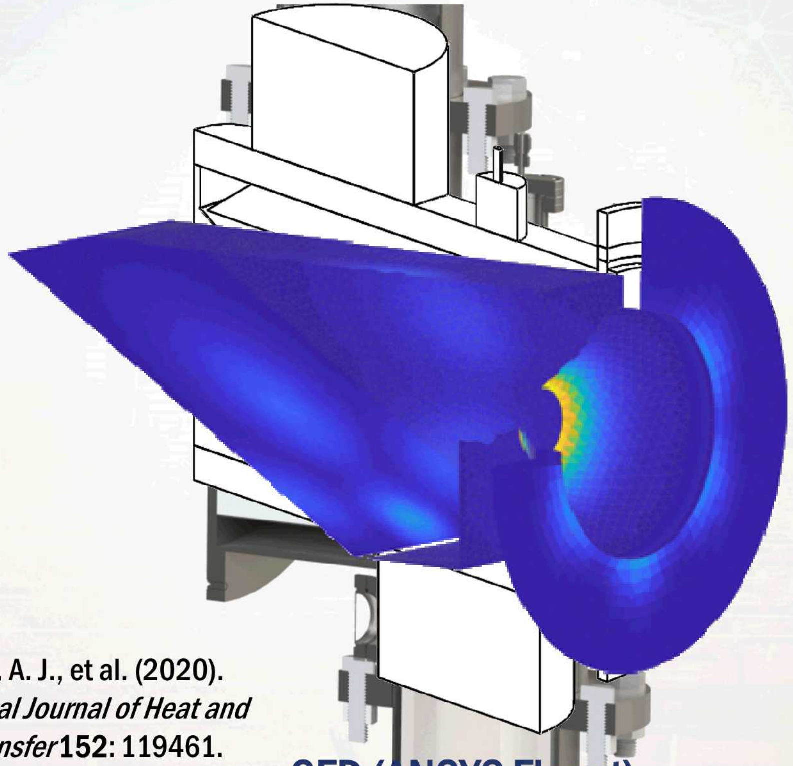
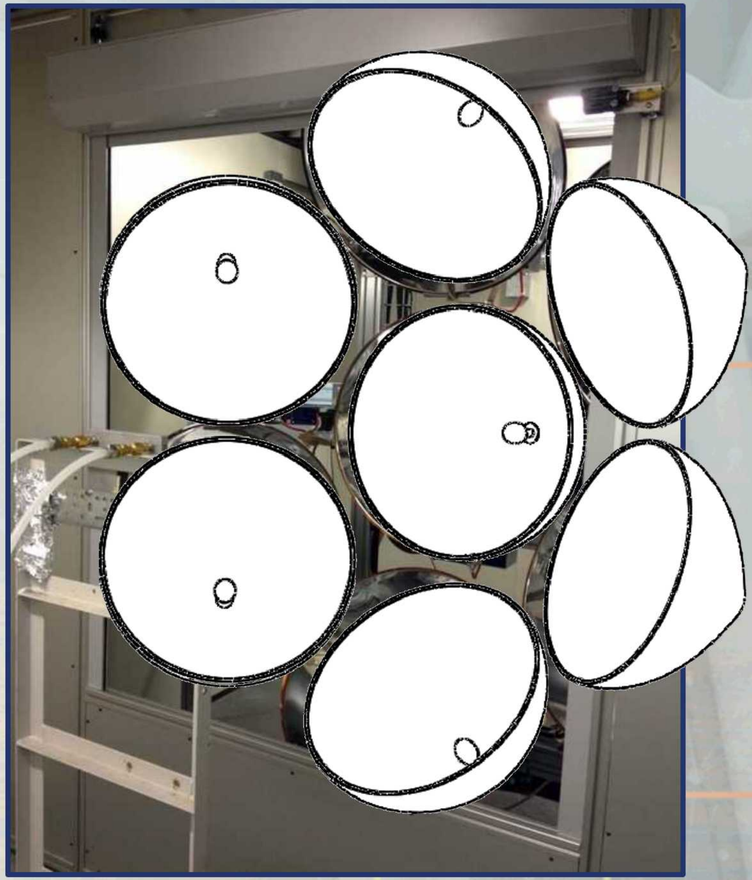
Example System



Schrader, A. J., et al. (2020). *International Journal of Heat and Mass Transfer* 152: 119461.

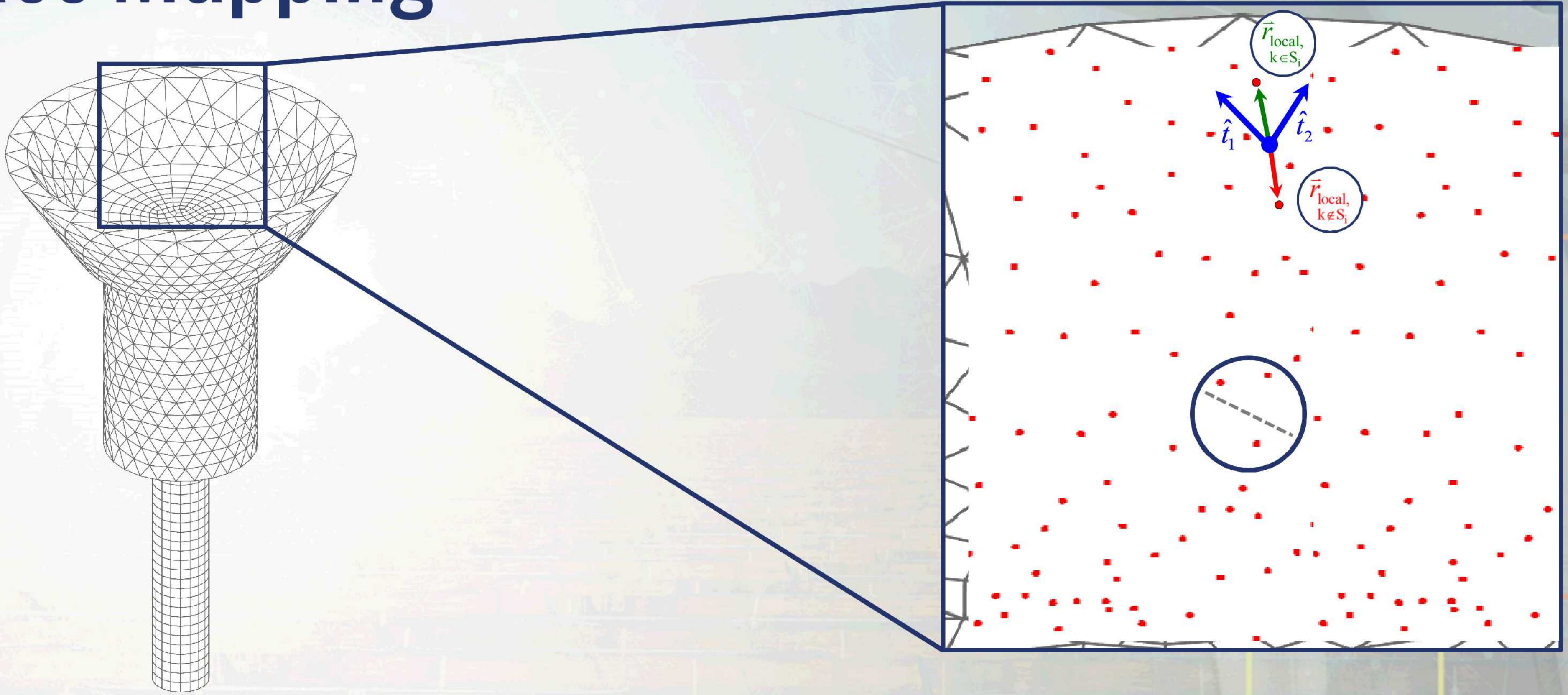
CFD (ANSYS Fluent)



Monte Carlo Ray Tracing

Direct Mapping Method

Surface Mapping



Volume Mapping

Method Definition

Surface Mapping

$$\vec{r}_{\text{local}} = at_1 + bt_2$$

$$S_{\text{i}} = \left\{ k = 1, 2, \ldots, N_{\text{rays}} \,\middle|\, \begin{array}{l} a_{\text{i,k}}, b_{\text{i,k}} > 0, \\ a_{\text{i,k}} + b_{\text{i,k}} \le 1 \end{array} \right\}$$

$$q''_{\text{sun,i}} = (\alpha H_0)_{\text{sun,i}} = \frac{1}{A_{\text{s,i}}} \sum_{\text{k} \in \text{S}_{\text{i}}} \dot{E}_{\text{k}}$$

$$-k_{\text{n,i}} \left.\frac{\partial T}{\partial n}\right|_{\text{s,i}} + q''_{\text{sun,i}} = U_{\text{i}} \left(T_{\text{s,i}} - T_{\infty,\text{i}} \right) + q''_{\text{R,i}}$$

Volume Mapping

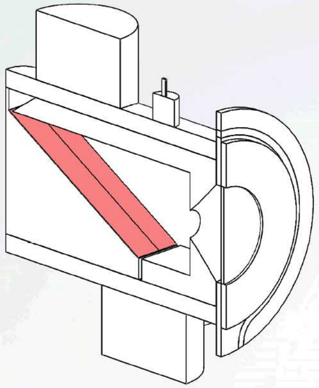
$$\vec{r}_{\text{local}} = at_1 + bt_2 + ct_3$$

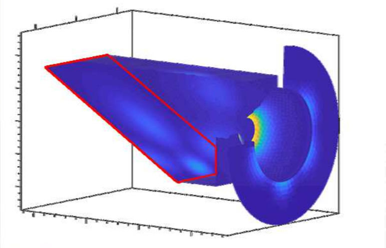
$$S_{\text{i}} = \left\{ k = 1, 2, \ldots, N_{\text{rays}} \,\middle|\, \begin{array}{l} a_{\text{i,k}}, b_{\text{i,k}}, c_{\text{i,k}} > 0, \\ a_{\text{i,k}} + b_{\text{i,k}} + c_{\text{i,k}} \le 1 \end{array} \right\}$$

$$\dot{q}'''_{\text{sun,i}} = \left(\kappa \int_{4\pi} I(s')\, d\Omega' \right)_{\text{sun,i}} = \frac{1}{V_{\text{i}}} \sum_{\text{k} \in \text{S}_{\text{i}}} \dot{E}_{\text{k}}$$

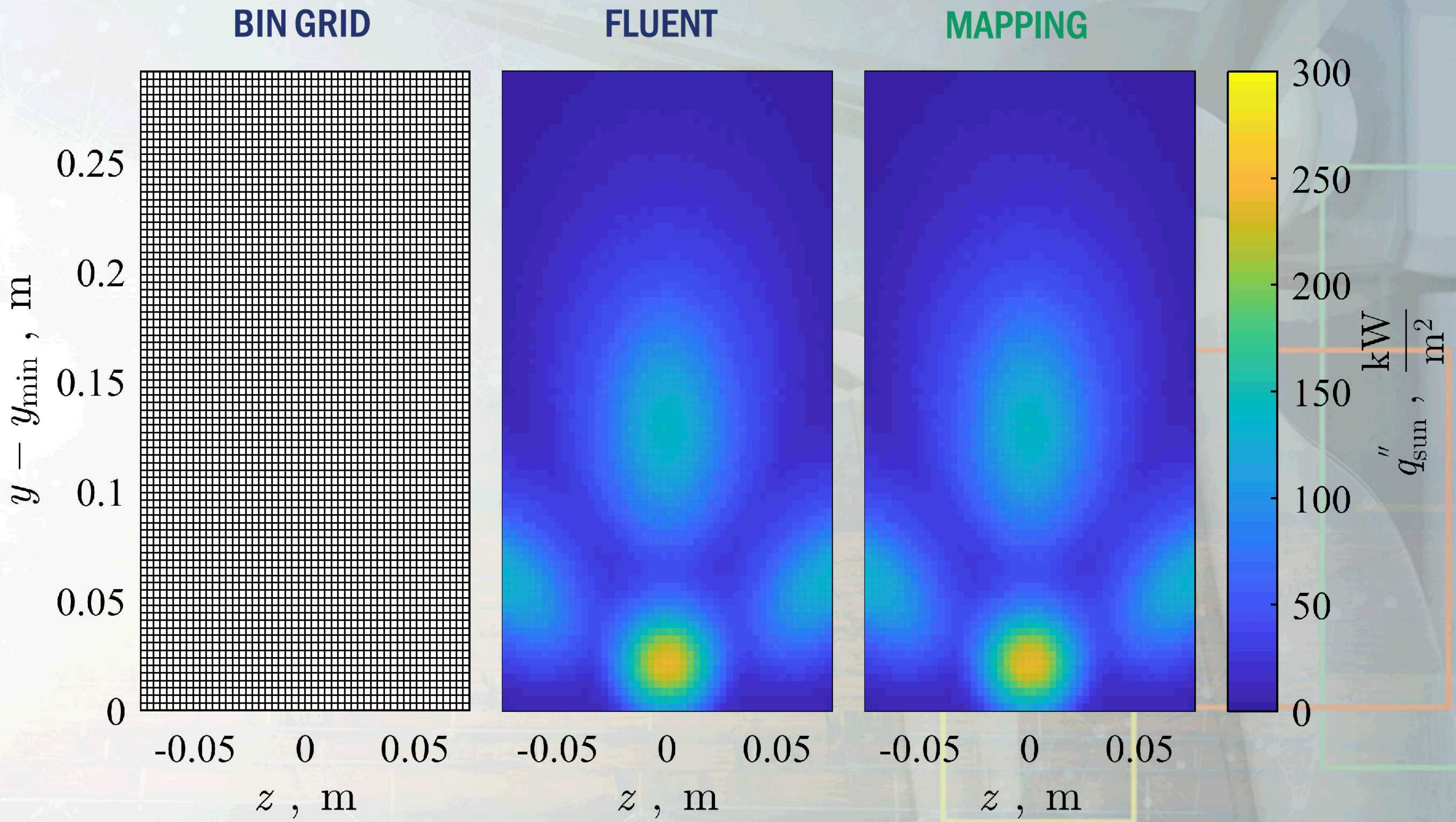
$$\frac{\partial E_{\text{i}}}{\partial t} + \nabla \cdot \left(\rho \vec{V} h \right)_{\text{nb,i}} = \nabla \cdot \left(k \nabla T_{\text{i}} \right) + q'''_{\text{sun,i}} + q'''_{\text{R,i}}$$

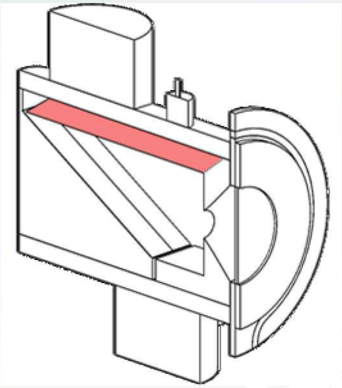
Case Studies

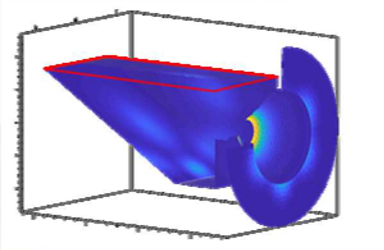


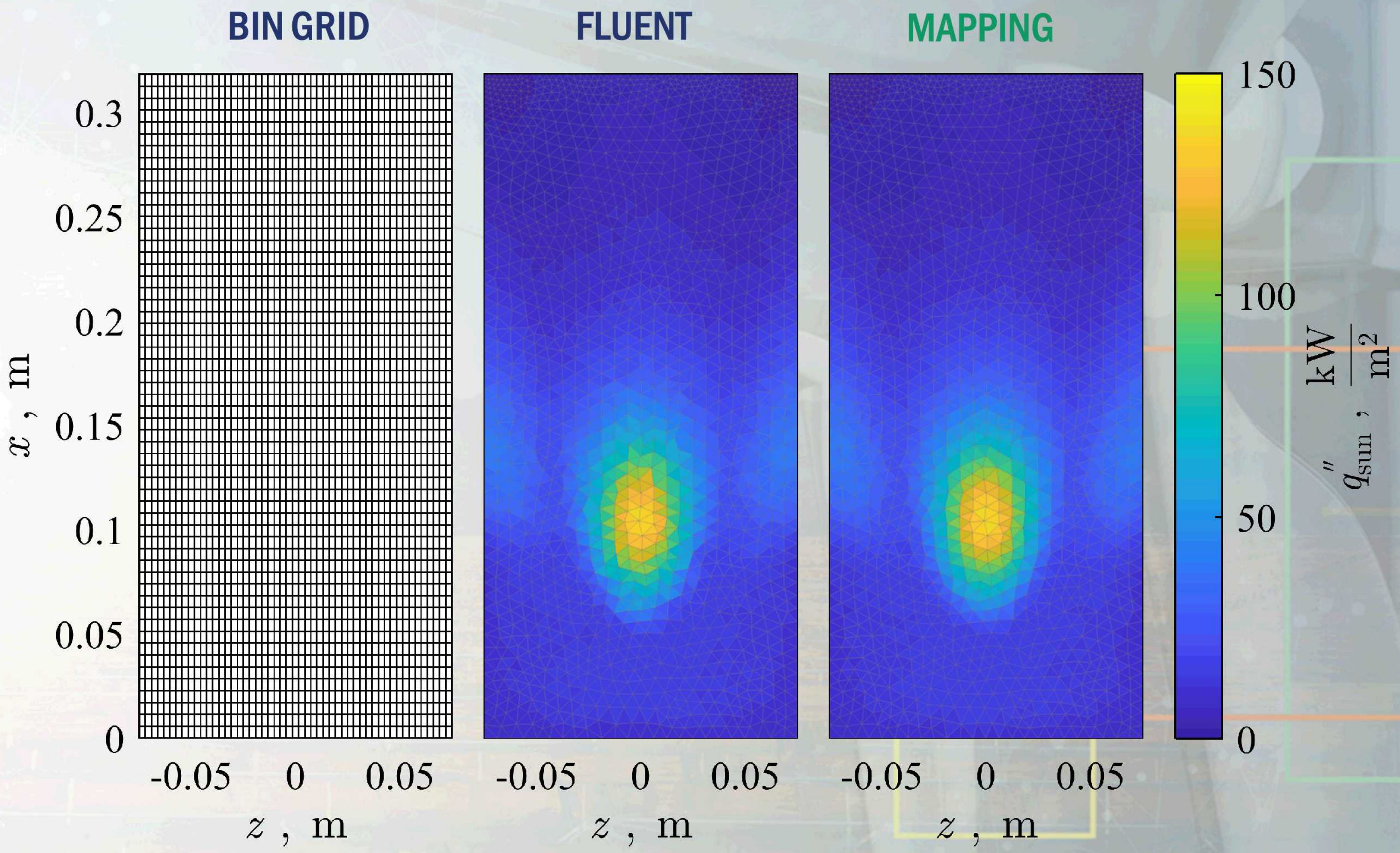


Exact grid alignment →
No interpolation error →
Identical results

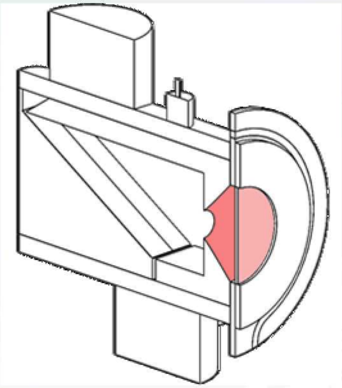


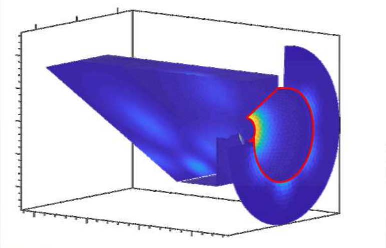


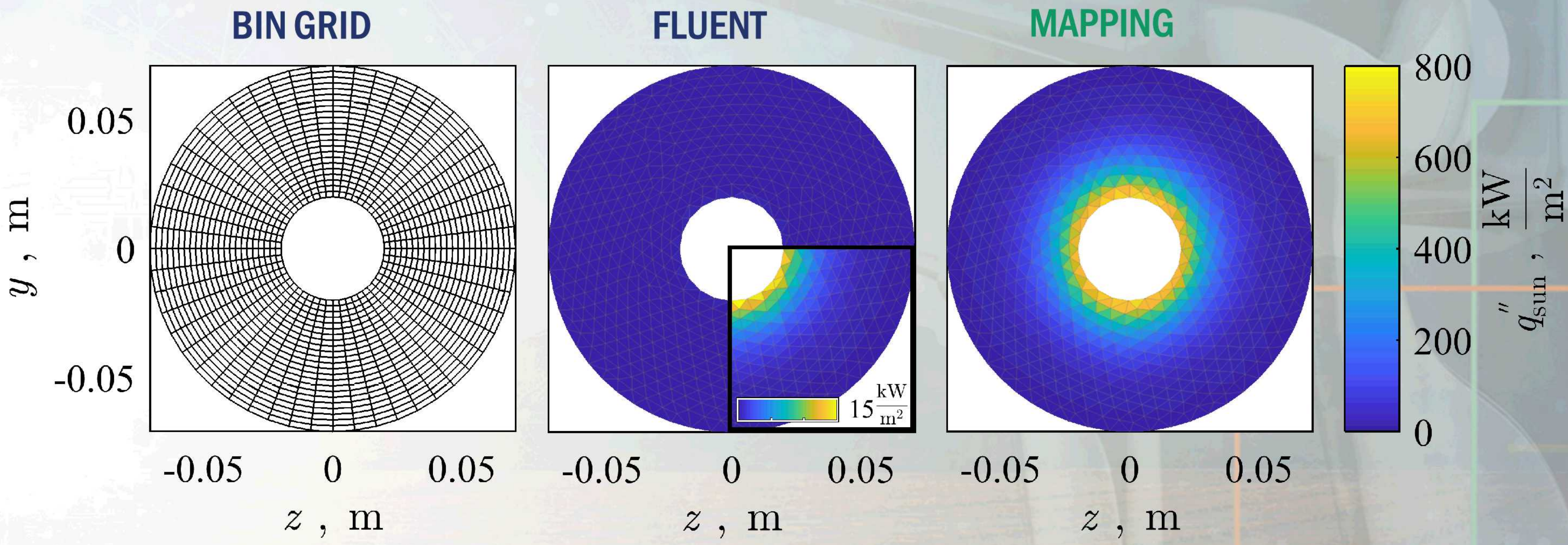




Direct Mapping Prevents:
Unstructured mesh →
FLUENT interpolation error →
Some (minor) spatial distortion

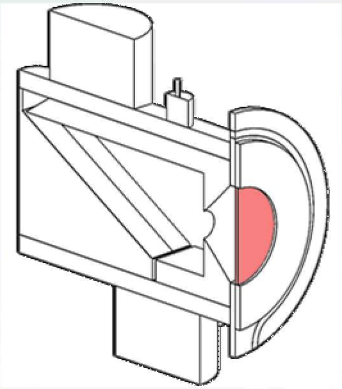


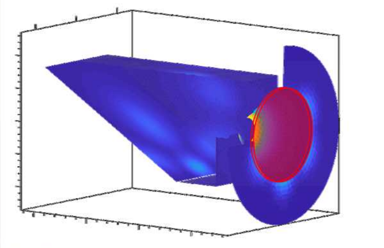


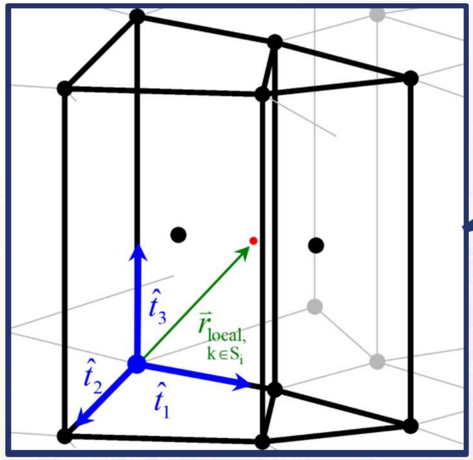


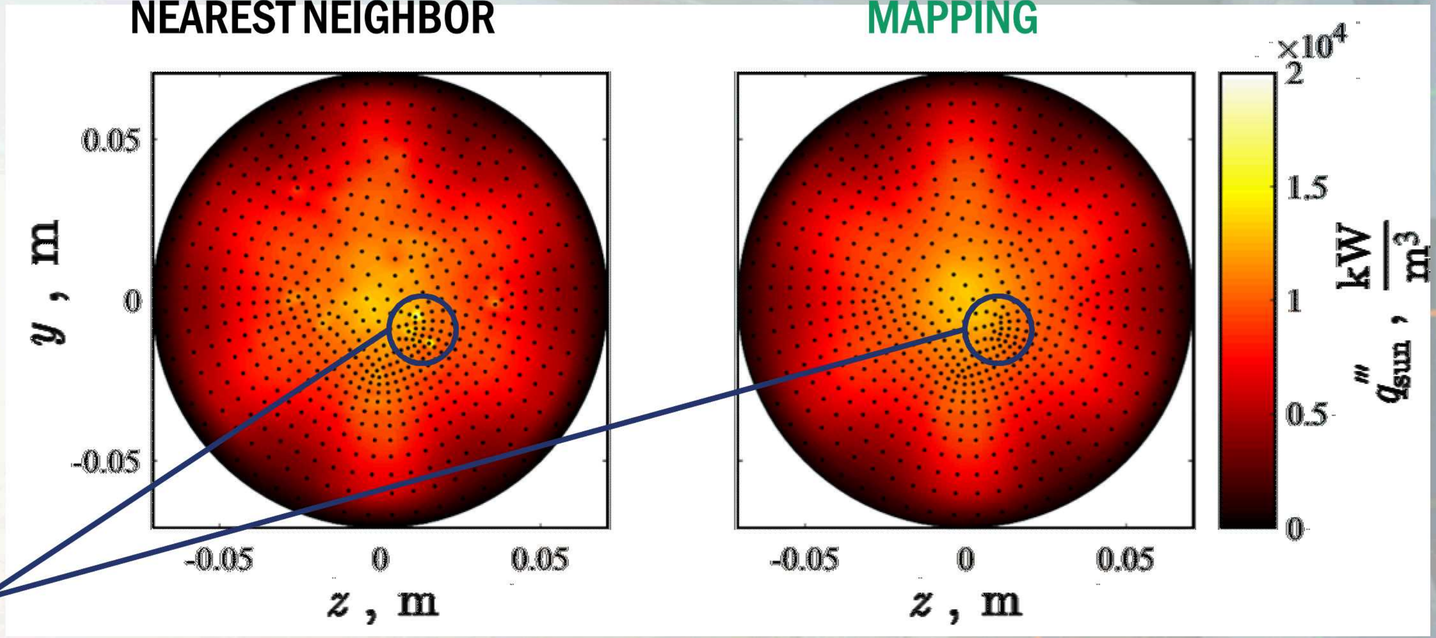
Direct Mapping Prevents:

High flux & flux gradient ⟶ Large interpolation error ⟶ Major energy loss!









Direct Mapping Prevents:

Cell volume distribution ⟶ Ray mis-sorting ⟶ Hot/cold spots

Summary

- Direct mapping method captures directional concentrated solar inputs
- Highly generalizable algorithm outlined
- Method is energy conservative and preserves spatial flux
- Direct mapping may mitigate spatial errors and prevent significant energy loss in solar receivers/reactors

Publications

- Bush, H. E. S., A.J.; Loutzenhiser, P.G (2020). Pairing directional solar inputs from ray tracing to solar receiver/reactor heat transfer models on unstructured meshes: Development and case studies. ASME 2020 14th International Conference on Energy Sustainability. Denver, CO, USA, ASME.
- Schrader, A. J., et al. (2020). "Aluminum-doped calcium manganite particles for solar thermochemical energy storage: Reactor design, particle characterization, and heat and mass transfer modeling." International Journal of Heat and Mass Transfer **152**: 119461.
- Schrader, A. J., et al. (2020). "Experimental demonstration of a 5 kWth granular-flow reactor for solar thermochemical energy storage with aluminum-doped calcium manganite particles." Applied Thermal Engineering **173**: 115257.
- Bush, H. E. (2019). Development and Characterization of Novel Reduction-Oxidation Active Materials for Two-Step Solar Thermochemical Cycles. G. W. Woodruff School of Mechanical Engineering. Atlanta, Georgia, USA, Georgia Institute of Technology. **PhD Mechanical Engineering:** 205.
- Bush, H. E., et al. (2017). "Design and Characterization of a Novel Upward Flow Reactor for the Study of High-Temperature Thermal Reduction for Solar-Driven Processes." Journal of Solar Energy Engineering **139**(5): 051004-051004-051011.

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NNSA
National Nuclear Security Administration

For More Information:

H. Evan Bush
Postdoctoral Appointee
Sandia National Labs

hebush@sandia.gov