Coupled Optical-CFD/HT Analysis of a Pressurized Cavity-Air-Receiver for Concentrating Solar Power

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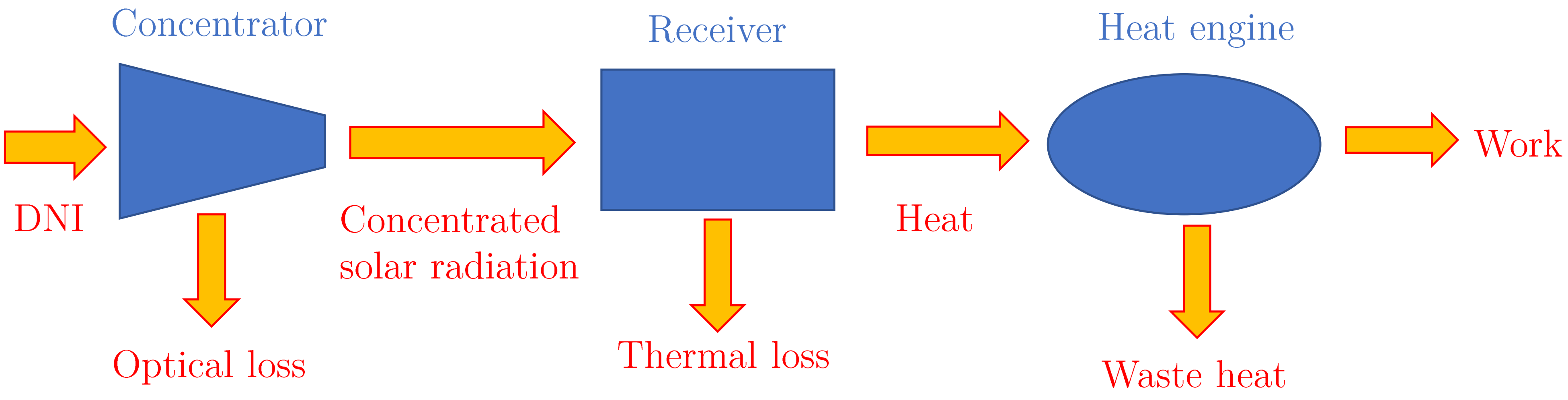
Outline

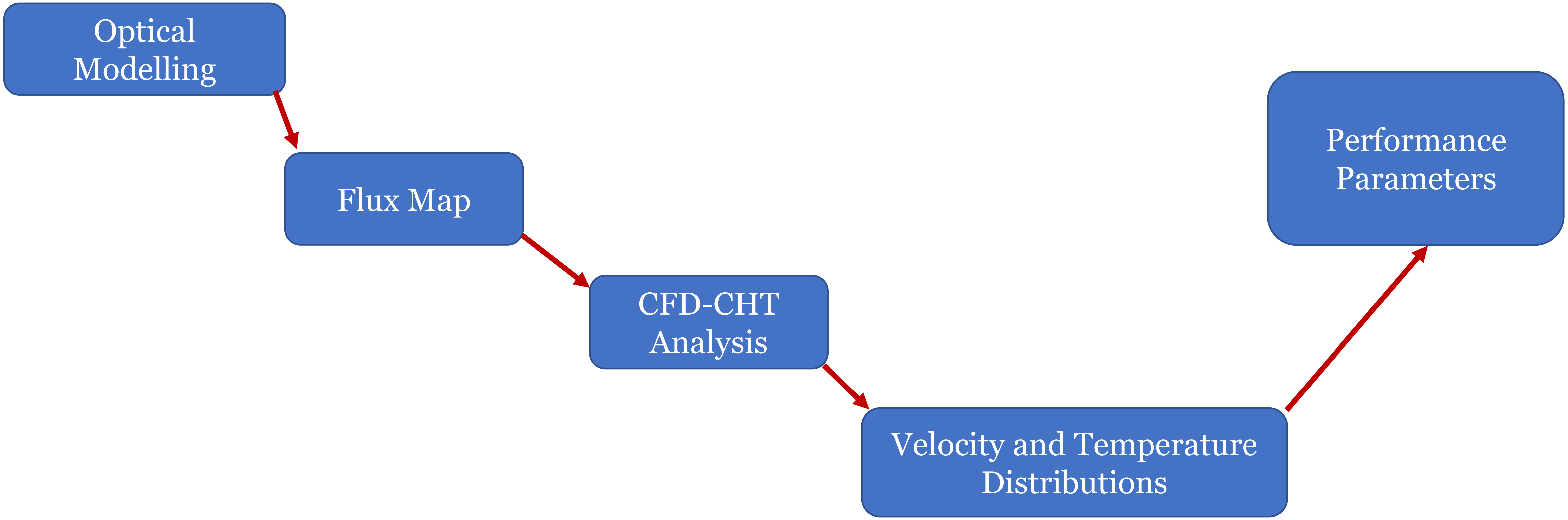
- Introduction
- Optical modelling of Scheffler concentrator
- Cavity-air-receiver modelling
- Validation
- Results and Conclusions

Introduction

General layout of energy conversion steps for CSP



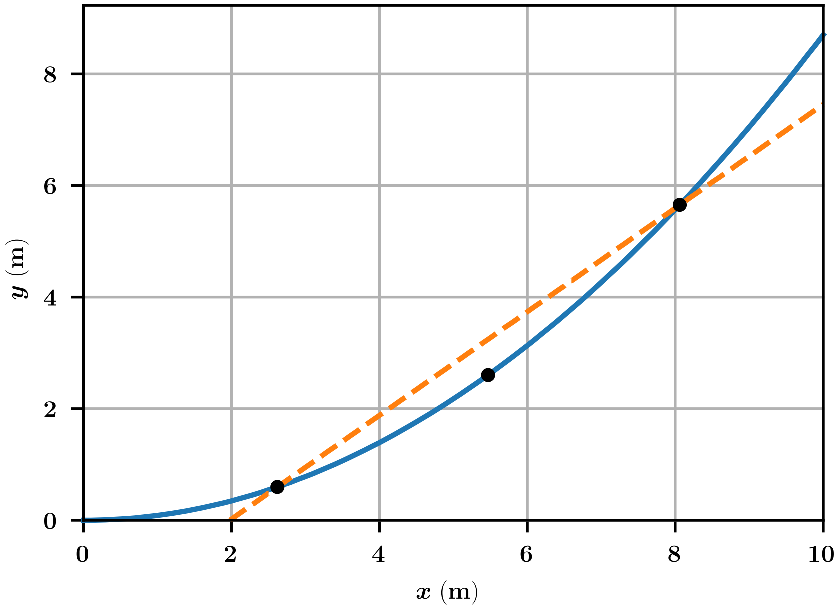
Receiver Modelling Steps



Optical modelling of Scheffler concentrator

Scheffler concentrator

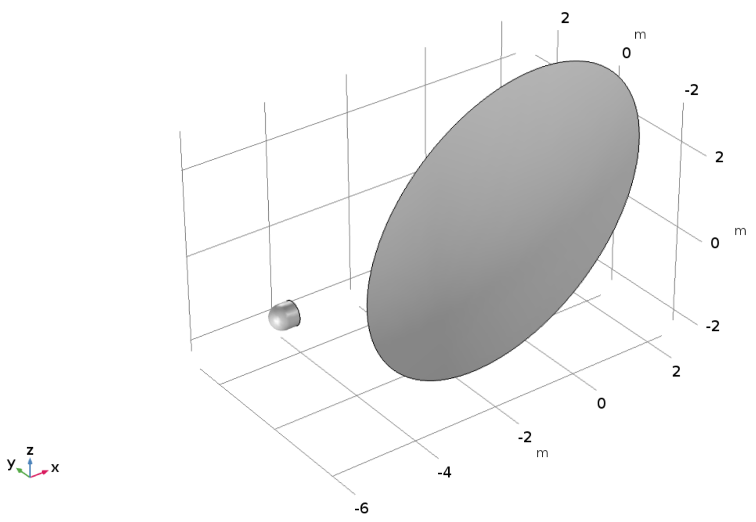
32 m^2 fixed focus Scheffler concentrator installed at ICER, IISc.

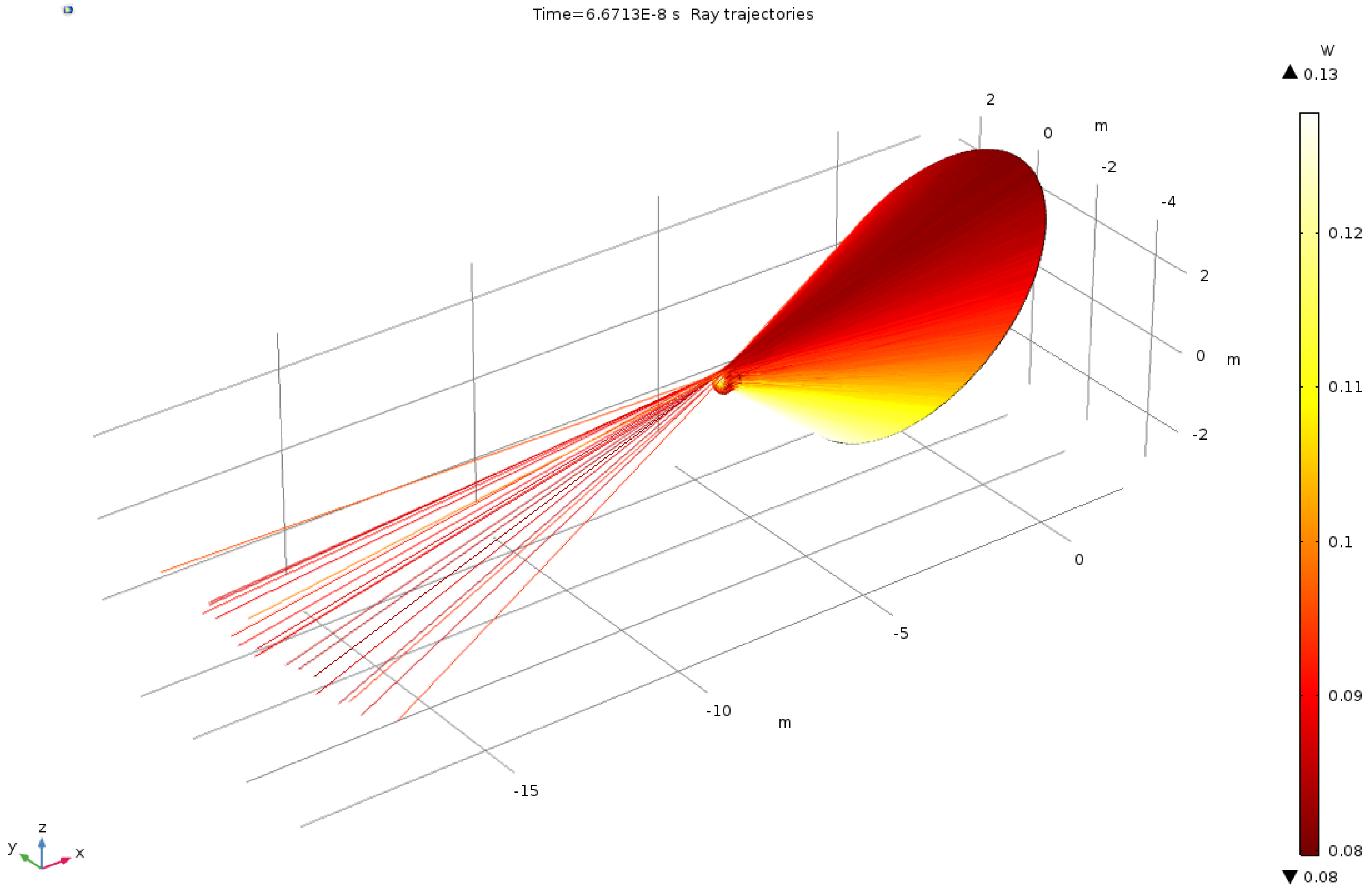


Parabolic curve whose lateral sections forms part of Scheffler dish.

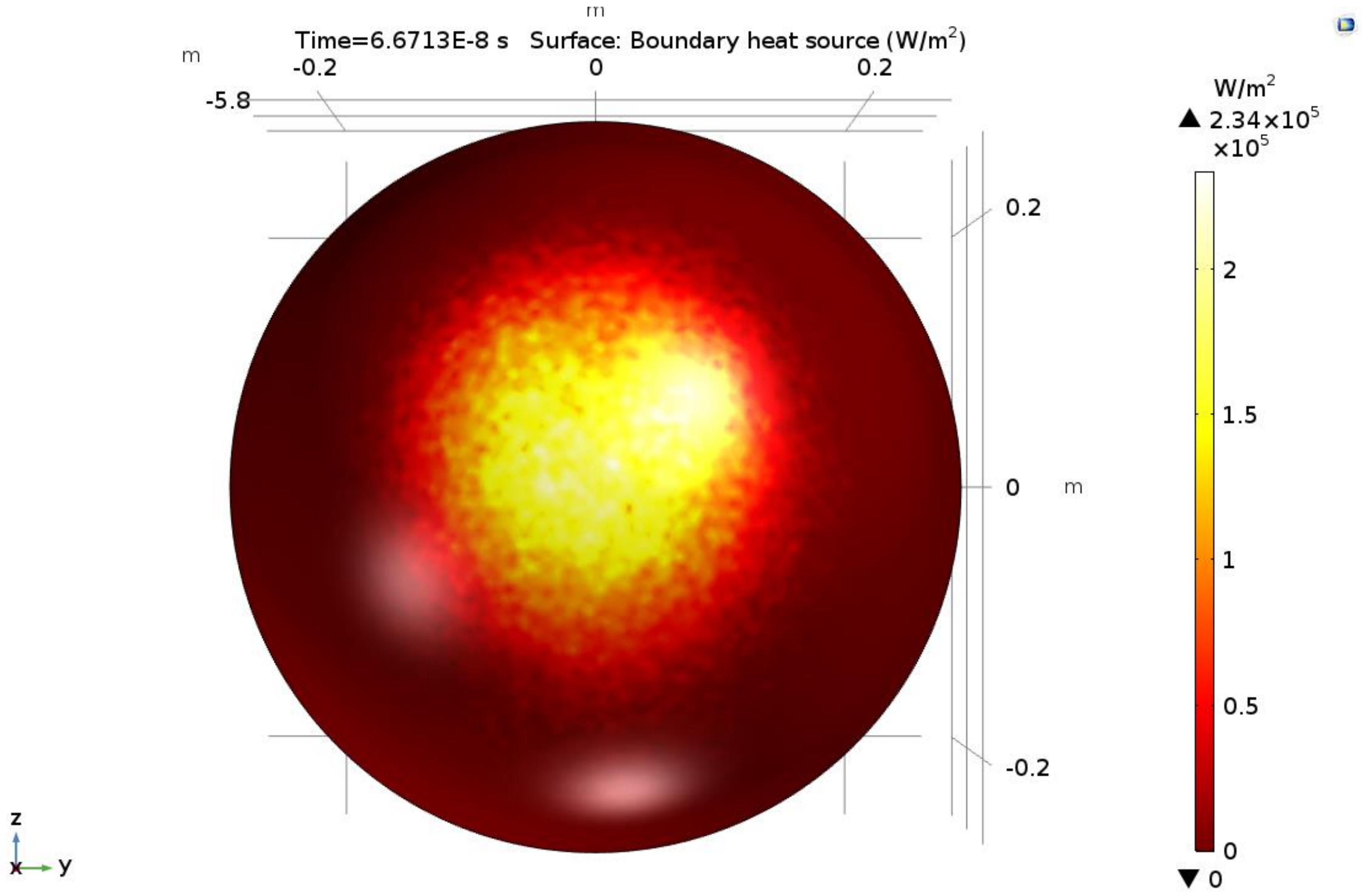
Ray Tracing Analysis

- Assumptions: Scheffler surface reflects specularly with surface slope error of 5 mrad and $\lambda \ll a$.
- Rays terminate at the cavity surface.
- Governing Equation: $\frac{d\boldsymbol{k}}{dt} = -\frac{\partial \omega}{\partial q}$; $\frac{d\boldsymbol{q}}{dt} = \frac{\partial \omega}{\partial k}$; $\mathbf{k}$ = wave vector, $\mathbf{q}$ = position vector.





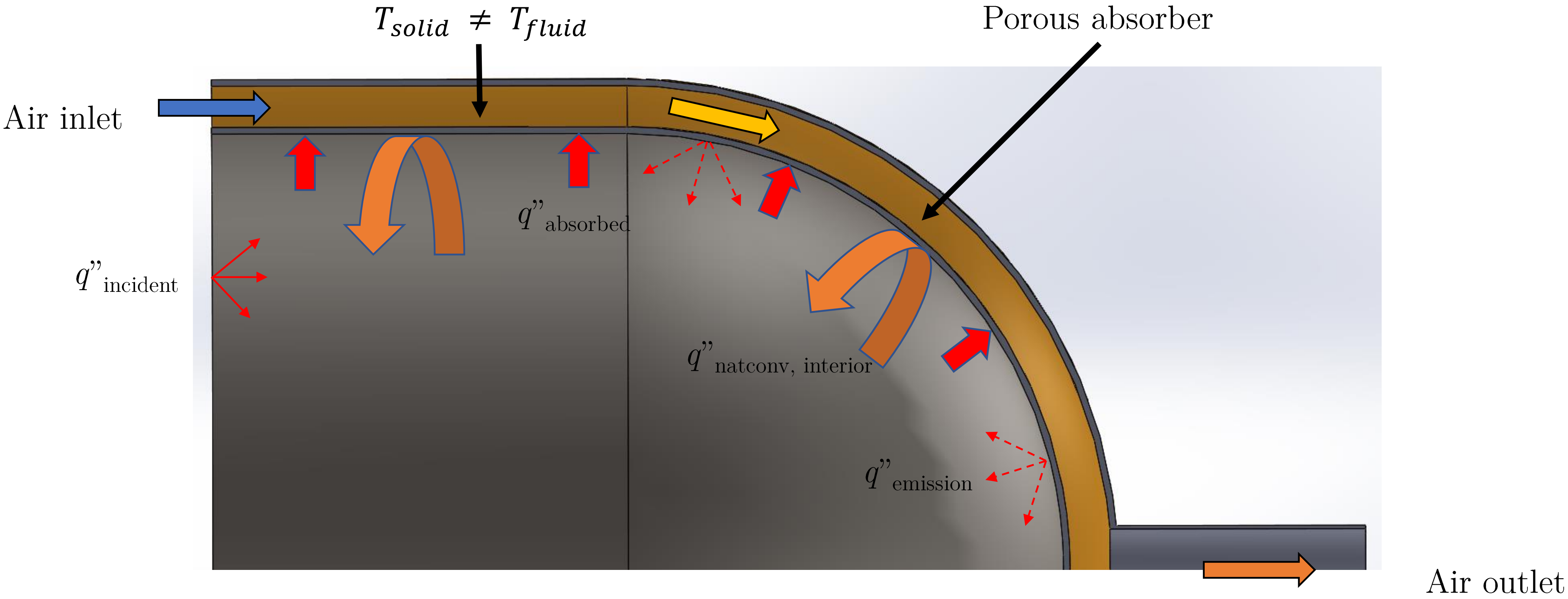
Ray tracing with 10^5rays from Scheffler surface with slope error 5 mrad onto the receiver cavity surface.



Flux map on the cavity surface

Cavity-air-receiver modelling

Heat transfer mechanism in cavity receiver



Receiver Loss modelling

- Natural convection loss from cavity surface : Modelled using Stine and McDonald[1] correlation for Nusselt number,

$$Nu = 0.088 * Gr_L^{\frac{1}{3}} * (\frac{T_w}{T_\infty})^{0.18} * cos\theta^{2.47} * (\frac{D_{aperture}}{L})^s$$

$$s = 1.12 - 0.982 * (\frac{D_{aperture}}{L})$$

- Emissivity of the stainless steel surface coated with selective coating is assumed 0.3[2] to model the reradiation loss from the heated cavity surface.

[1] Leibfried, U., & Ortjohann, J. (1995). Convective Heat Loss from Upward and Downward-Facing Cavity Solar Receivers: Measurements and Calculations. *Journal of Solar Energy Engineering*, *117*(2), 75. https://doi.org/10.1115/1.2870873
[2] https://www.solec.org/wp-content/uploads/2014/02/SOLKOTEbrochure.pdf

Porous Medium Modelling

- The porous medium is assumed to be homogeneous and isotropic in nature.
- The flow through porous medium is modelled using Brinkman equations with specified Forchheimer drag coefficient[3].
- Local thermal non-equilibrium model is used for modelling heat transfer in the porous medium.
- The interstitial heat transfer coefficient, h_{sf} is obtained from the correlation, $Nu_{sf} = 1.5590 + 0.5954 Re_p^{0.5626} Pr^{0.4720}$.

Hischier, I. (2012). Experimental and Numerical Analyses of a Pressurized Air Receiver for Solar-Driven Gas Turbines. Journal of Solar Energy Engineering, 134(2), 021003. https://doi.org/10.1115/1.4005446

Governing Equations

Continuity equation: $\nabla.(\rho\boldsymbol{u}) = \mathbf{0}$

Momentum equation: $\frac{\rho}{\epsilon_p}(\boldsymbol{u}.\nabla)\boldsymbol{u} = \left[-p\mathbf{I} + \frac{\mu}{\epsilon_p}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T)\right] - \left(\frac{\mu}{K} + \beta_F|\boldsymbol{u}|\right)\boldsymbol{u}$

Solid phase energy equation: $\nabla.\left(\theta_p k_{\boldsymbol{s}} \boldsymbol{\nabla}\mathrm{T}_{\boldsymbol{s}}\right) + h_{\mathrm{sf}}\left(\mathrm{T}_{\boldsymbol{f}} - \mathrm{T}_{\boldsymbol{s}}\right) = \mathbf{0}$

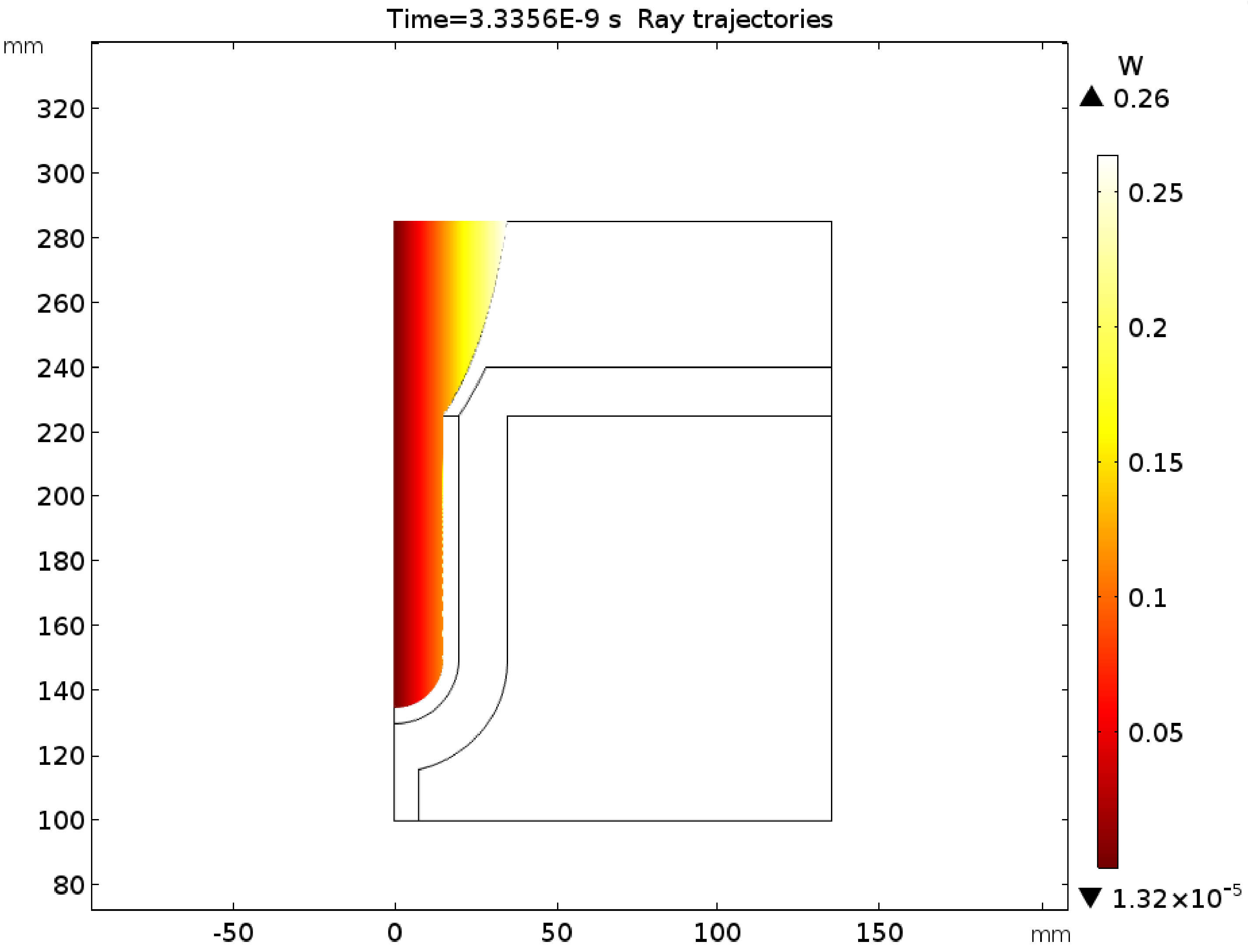
Fluid phase energy equation: $\epsilon_p \rho c_p \boldsymbol{u}_{\mathrm{f}}.\nabla\mathrm{T}_{\mathrm{f}} = \nabla.\left(\epsilon_p k_{\mathrm{f}} \boldsymbol{\nabla}\mathrm{T}_{\mathrm{f}}\right) + h_{\mathrm{sf}}(\mathrm{T}_{\boldsymbol{s}} - \mathrm{T}_{\mathrm{f}})$

Validation

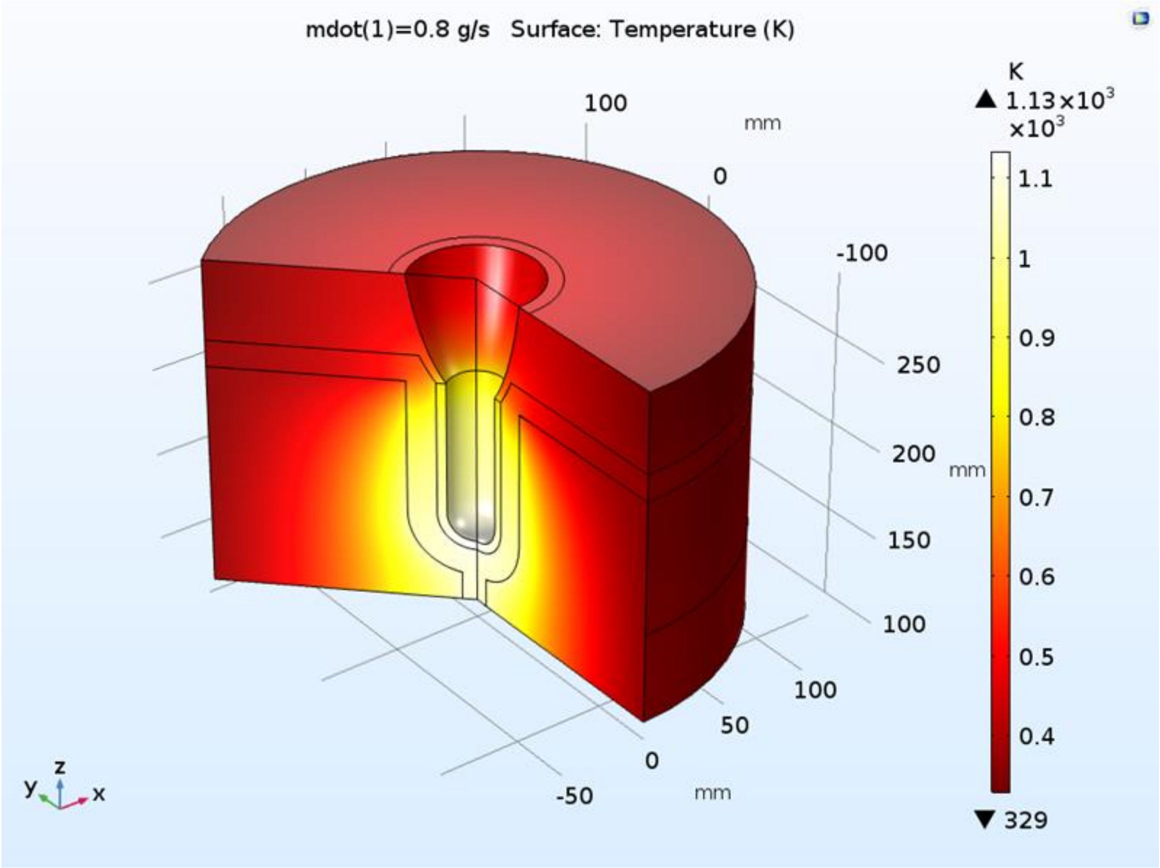
- COMSOL Multiphysics model is validated against two dimensional axisymmetric model of a 1.32kW cavity receiver done by Hischier et al.
- Pressure drop values are underpredicted by about 50% but is within the experimental error bar value while outlet air temperatures are overpredicted by about 15%.

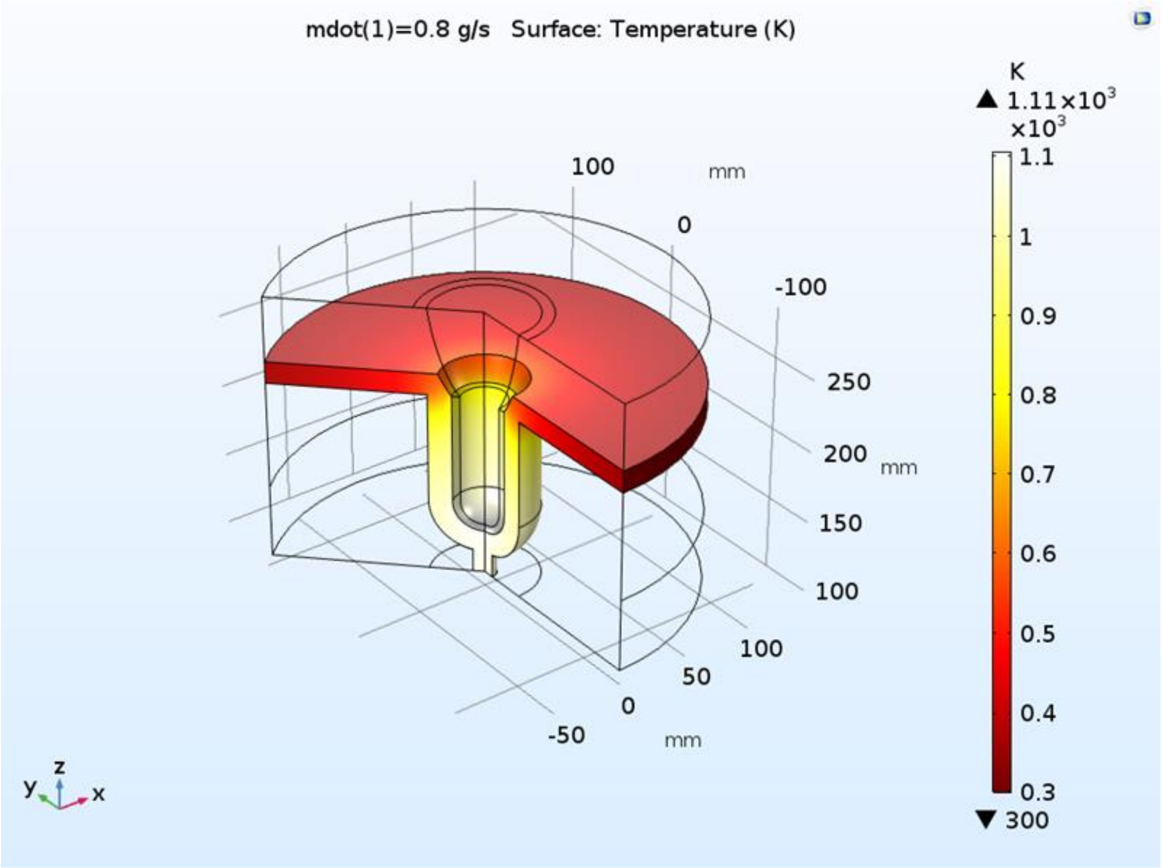
Hischier, I. (2012). *Experimental and Numerical Analyses of a Pressurized Air Receiver for Solar-Driven Gas Turbines*. Journal of Solar Energy Engineering, 134(2), 021003. https://doi.org/10.1115/1.4005446

2D-Axisymmetric Ray Tracing

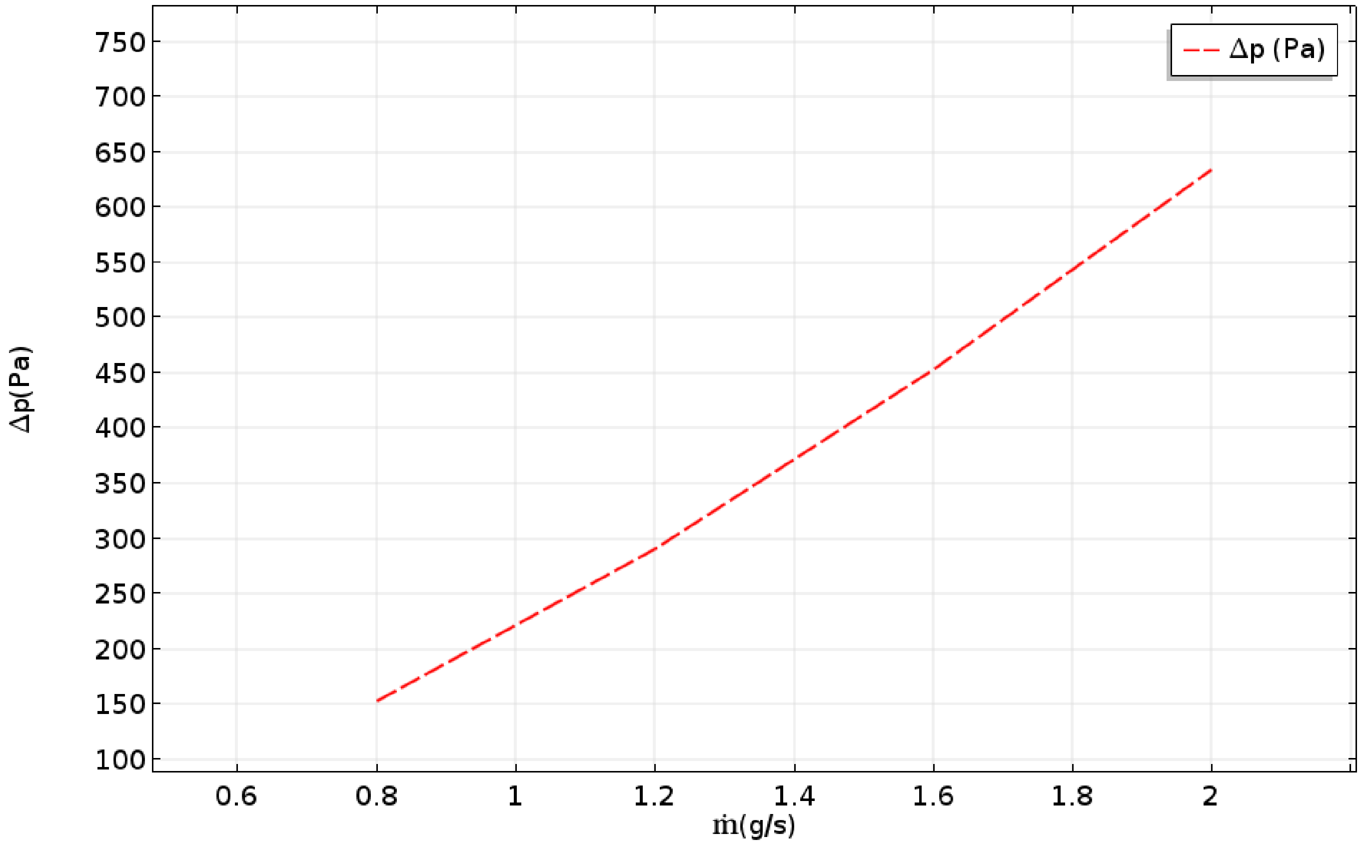


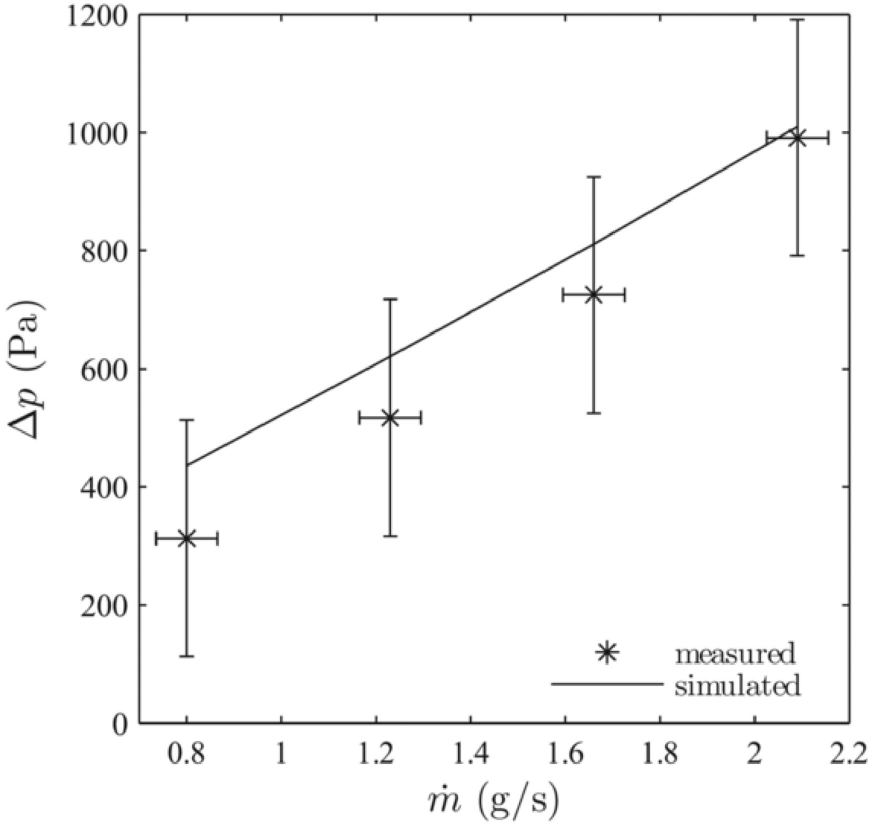
Porous solid and air temperature distribution



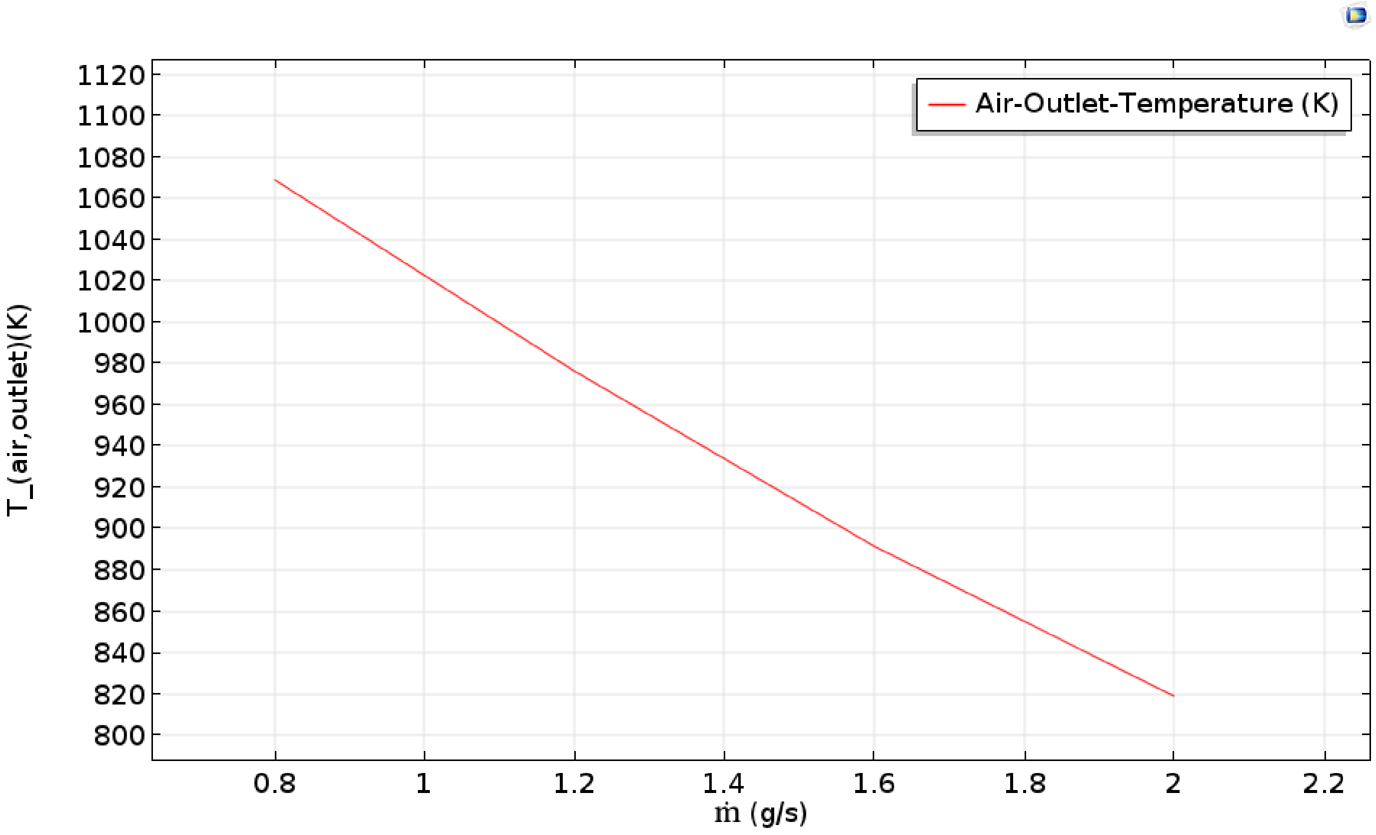


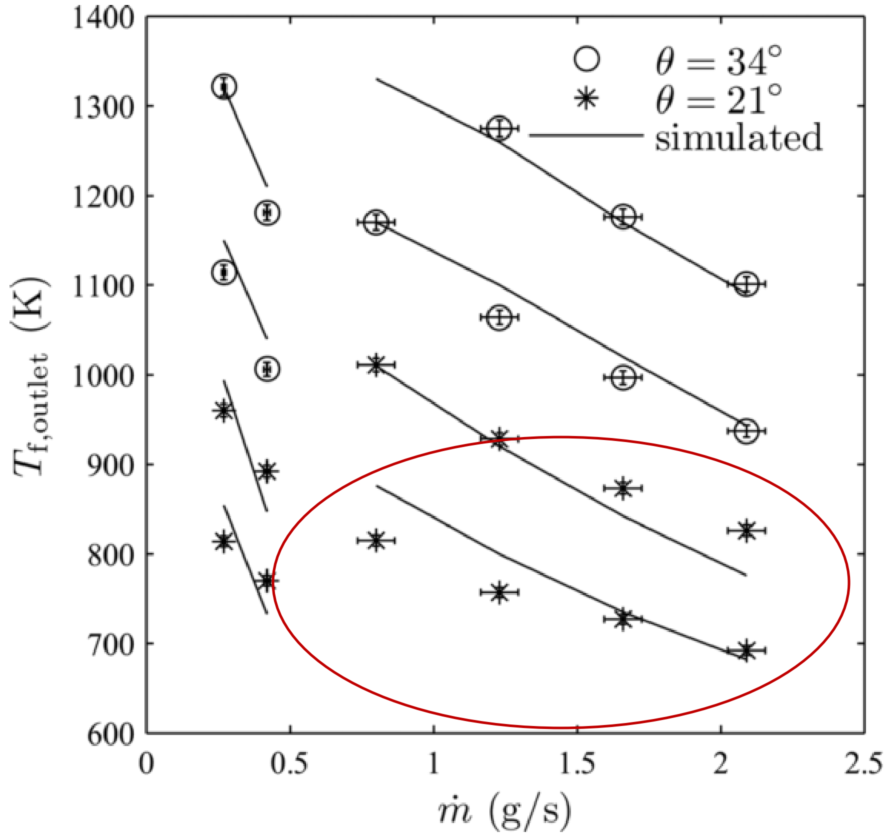
Mass flow rate vs Pressure drop





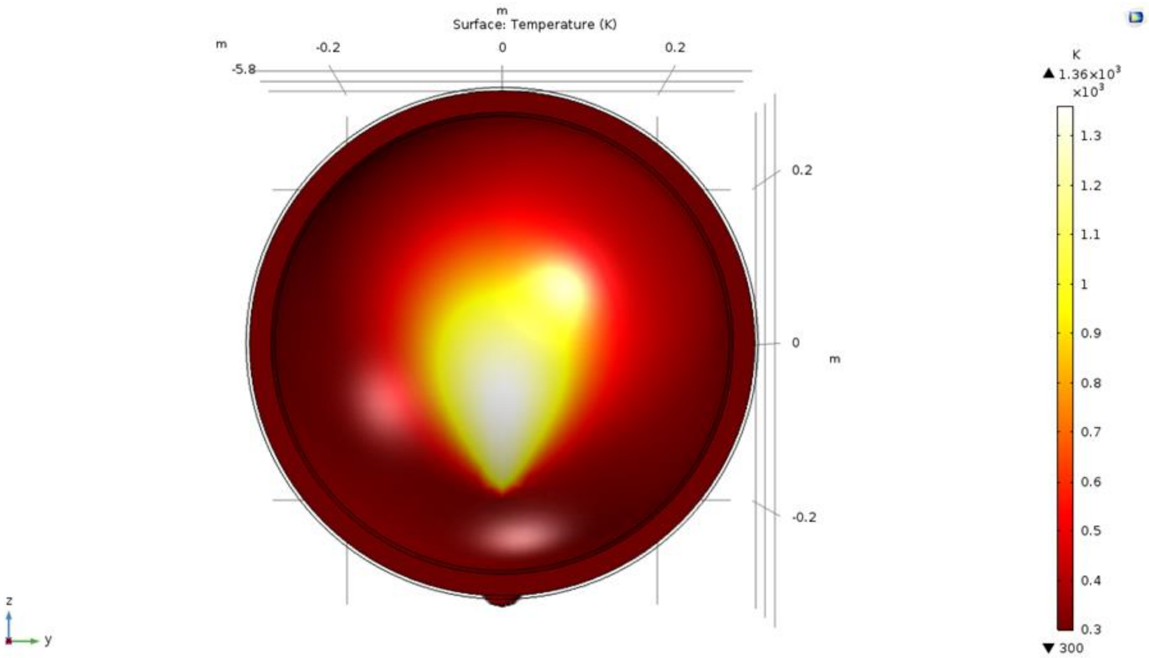
Outlet air temperature vs mass flow rate



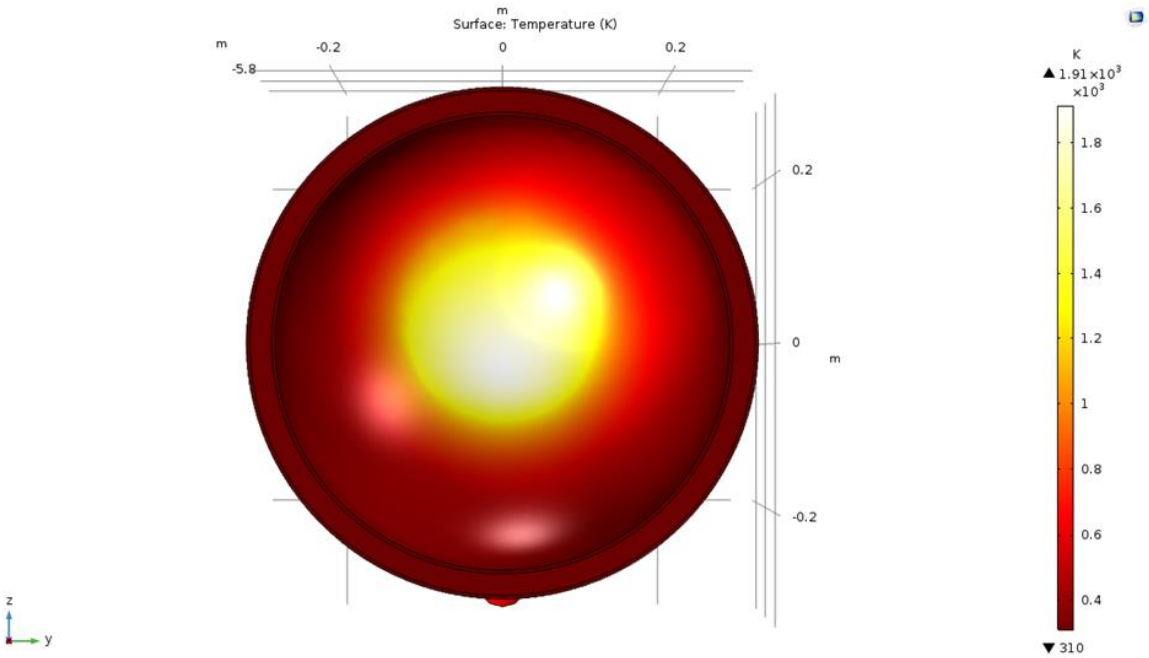


Results and Conclusions

Temperature distribution in the receiver

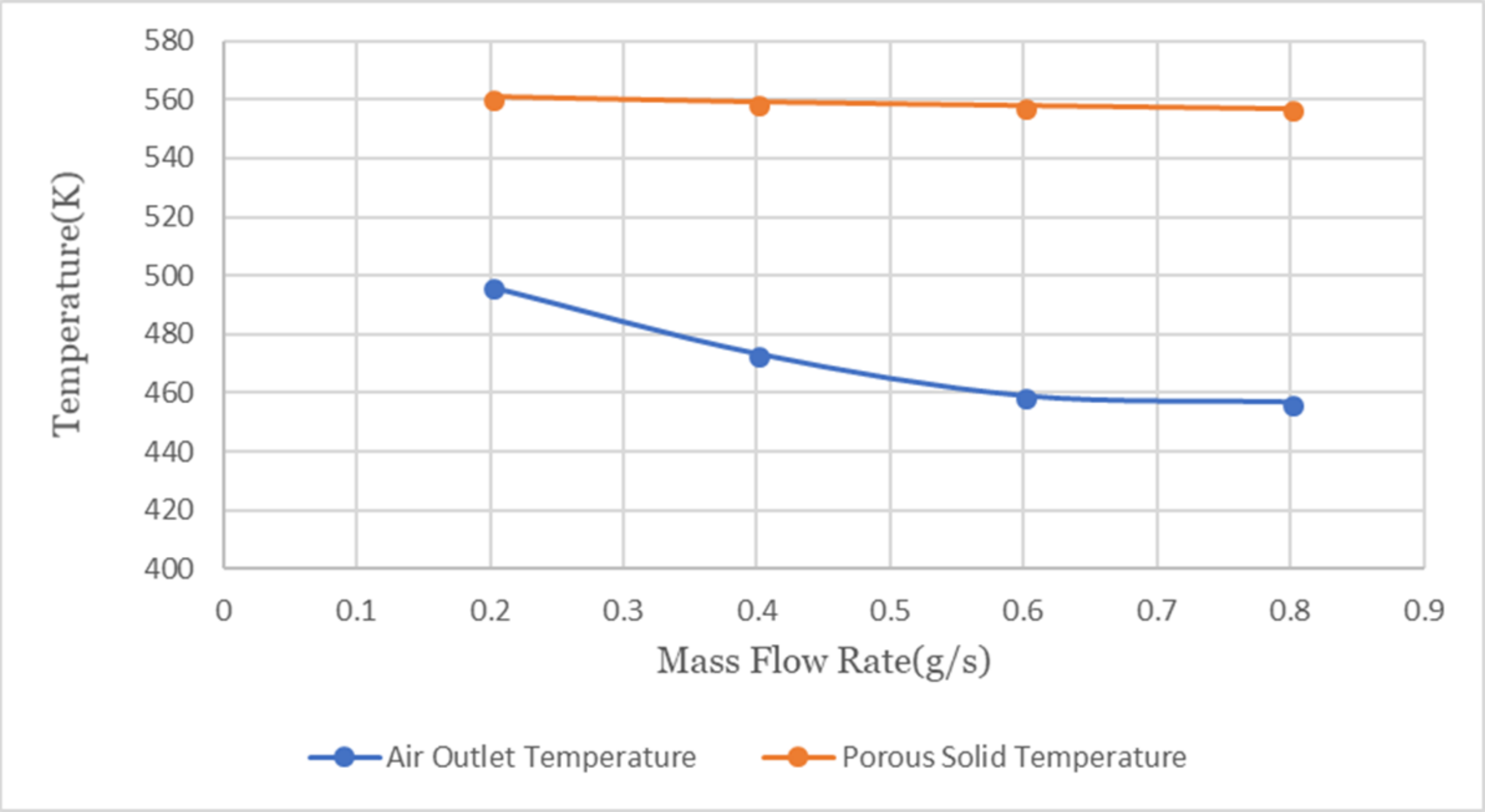


Air temperature distribution for $\dot{m} = 0.2$ g/s



Porous medium temperature distribution for $\dot{m} = 0.2$ g/s

Temperature vs mass flow rate plot



Conclusions

- Coupled optical-CFD/CHT analysis is carried out for 10kW cavity-air-receiver at 20bar absolute pressure.
- Modelling the flow and heat transfer through the porous domain provides guidelines for the receiver absorber design.
- Porous absorber should have thermal conductivity which decreases as temperature increases.
- Radiation transport in the porous domain becomes dominant at higher temperatures.

Receiver and Test Rig

Thank You