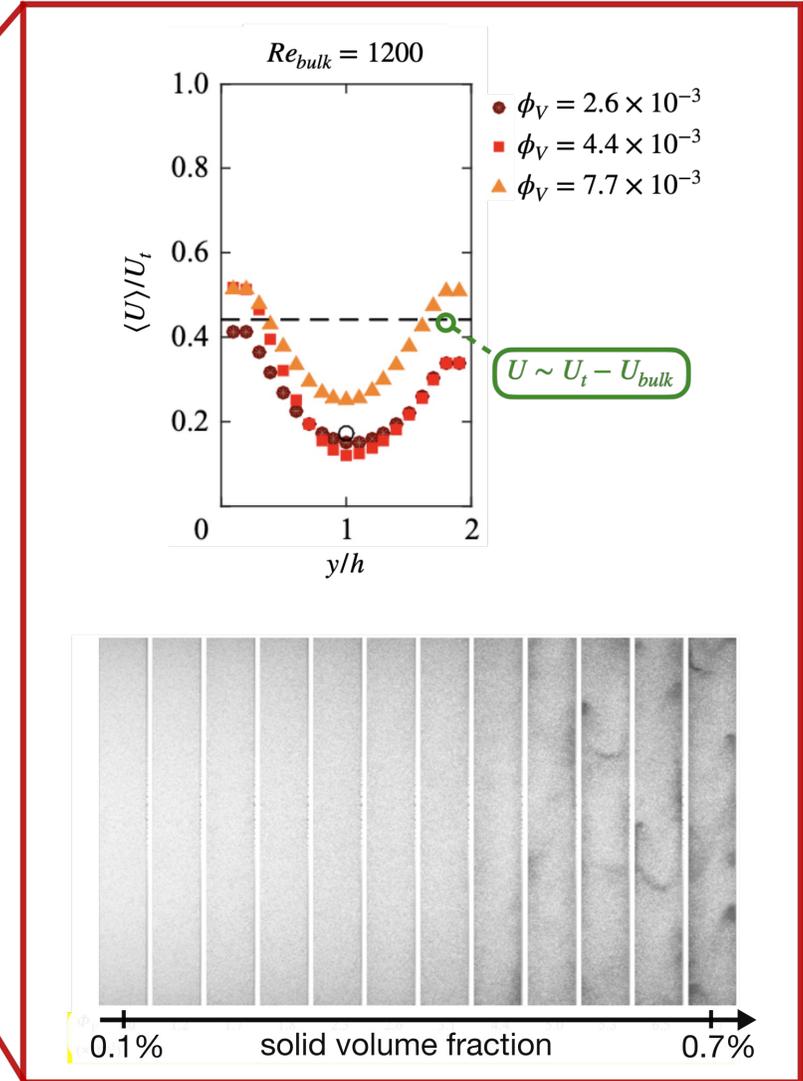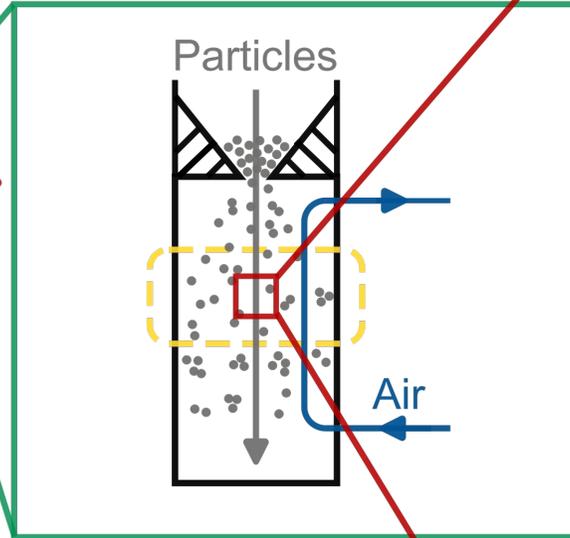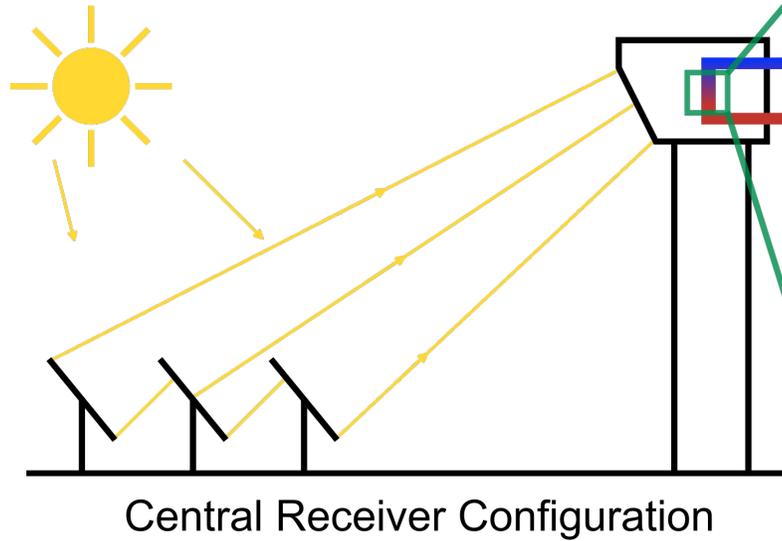# Development of a High-Temperature Counter-Flow Solar Particle Receiver

Anton Hartner, Filippo Coletti & Aldo Steinfeld

01. August 2023, Zurich

Introduction

Central Receiver Configuration

Particles

Air

$Re_{bulk} = 1200$

$\phi_V = 2.6 \times 10^{-3}$
$\phi_V = 4.4 \times 10^{-3}$
$\phi_V = 7.7 \times 10^{-3}$

$\langle U \rangle / U_t$

y/h

$U \sim U_t - U_{bulk}$

0.1%   solid volume fraction   0.7%

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Experimental Set-Up

1. Hopper
2. Orifice control
3. Air Out
4. Diffuser
5. Duct
6. Flow Conditioners
7. Air In
8. Basket
9. Scale

Particle Collecting System
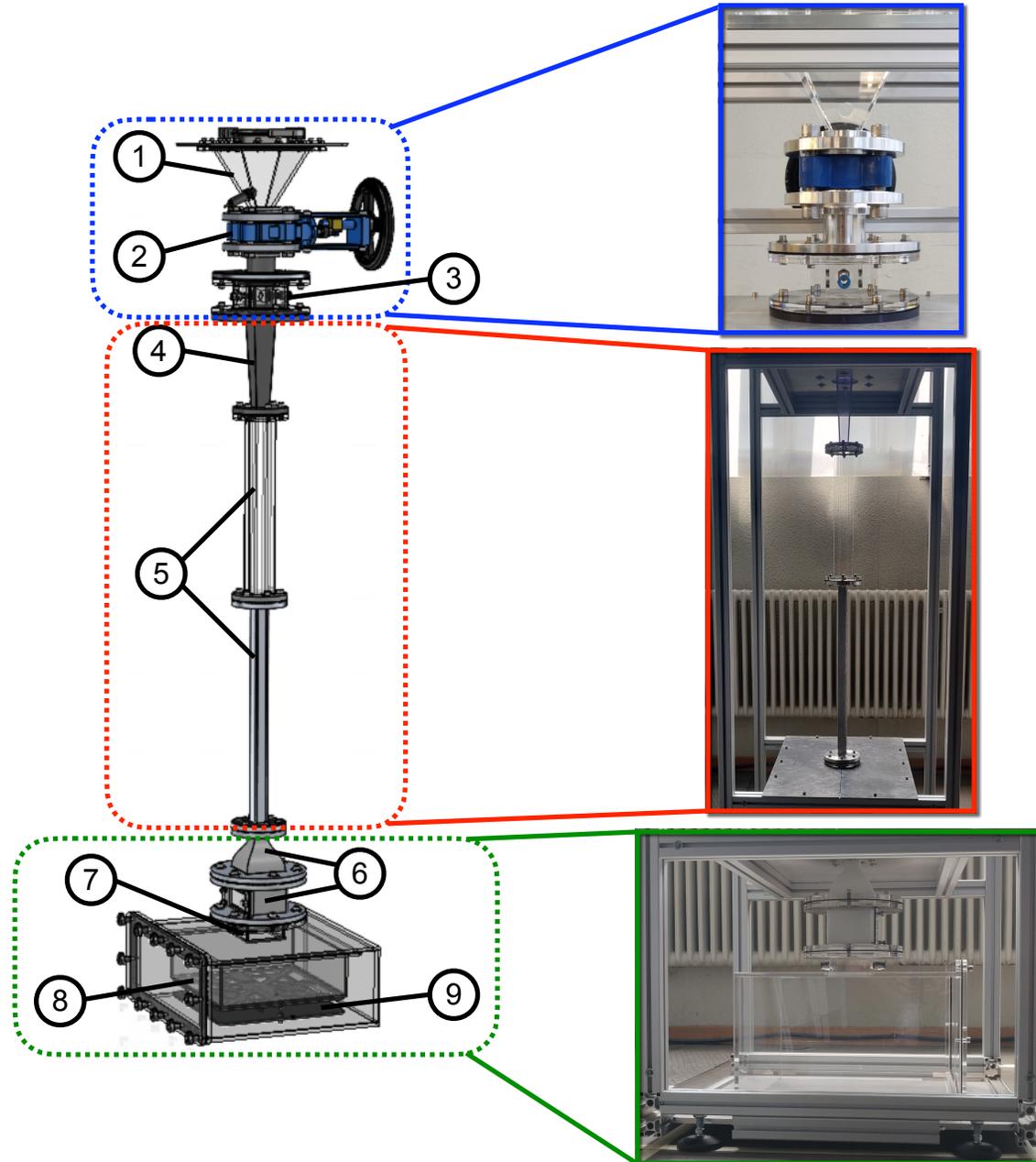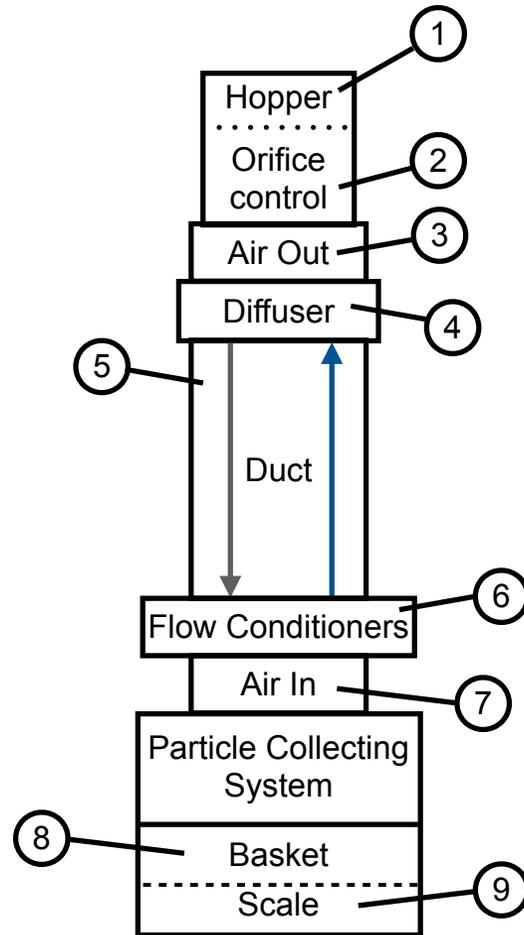
1D Heat Transfer Model – General
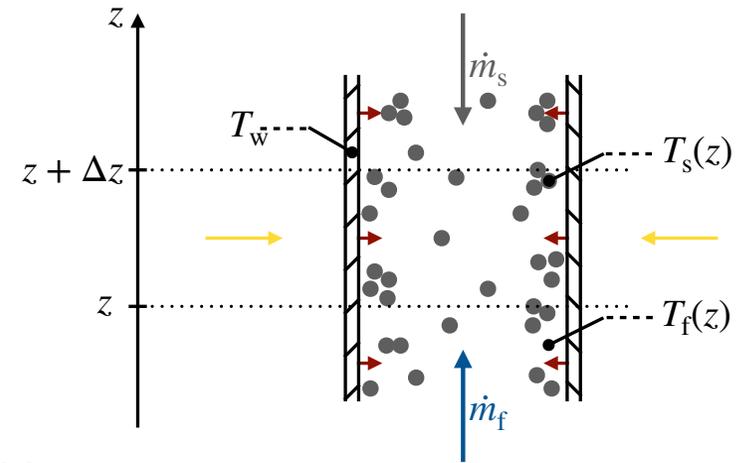

General Assumptions:

a. 1D problem along the z-direction
b. Steady state, no accumulation of heat
c. No pressure drop

Fluid Phase:

d. Non-participating medium
e. Conduction neglected
f. Convection: Fluid-Particles, Fluid-Wall

Solid Phase:

d. Participating medium
e. Inter-/ Intra-particle conduction neglected
f. Convection: Fluid-Particles

Energy Balances:

Fluid Phase:

$$\dot{m}_f c_{p,f} \frac{dT_f}{dz} = \underbrace{\frac{6\,\phi_{v,s}^2}{d_p} A_{cs,duct} h_{s-f}[T_s - T_f]}_{\text{heat exchange fluid - solid}} + \underbrace{h_{w-f}[T_w - T_f]}_{\text{heat exchange fluid - wall}}$$

where the first boxed term is **convection** and

Solid Phase:

$$-\dot{m}_s c_{p,s} \frac{dT_s}{dz} = -\frac{6\,\phi_{v,s}^2}{d_p} A_{cs,duct} h_{s-f}[T_f - T_s] - \frac{\dot{Q}_{rad}}{\Delta z} \quad \forall\, \dot{m}_s < 0$$

convection · heat exchange fluid - solid · radiative source term

1D Heat Transfer Model – Radiative Source Term

The radiative source term can be expressed by

$$\dot{Q}_{\text{rad}} = \underline{\nabla}q_{\text{r}}A_{\text{cs,duct}}\Delta z \quad \text{with} \quad \underline{\nabla}q_{\text{r}} = 4\pi \int_0^\infty a_\lambda \left[i'_{\lambda b}(S) - \bar{i}'_\lambda(S) \right]$$

with $\underline{\nabla}q_{\text{r}}$ being the divergence of the radiative flux. An expression for $\underline{\nabla}q_{\text{r}}$ can be found with the help of the radiative transfer equation

$$\frac{di'_\lambda}{dS} = -\text{Loss by absorption} + \text{Gain by emission} - \text{Loss by scattering} + \text{Gain by scattering}$$
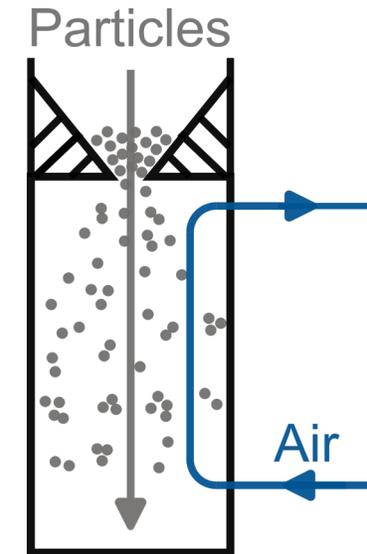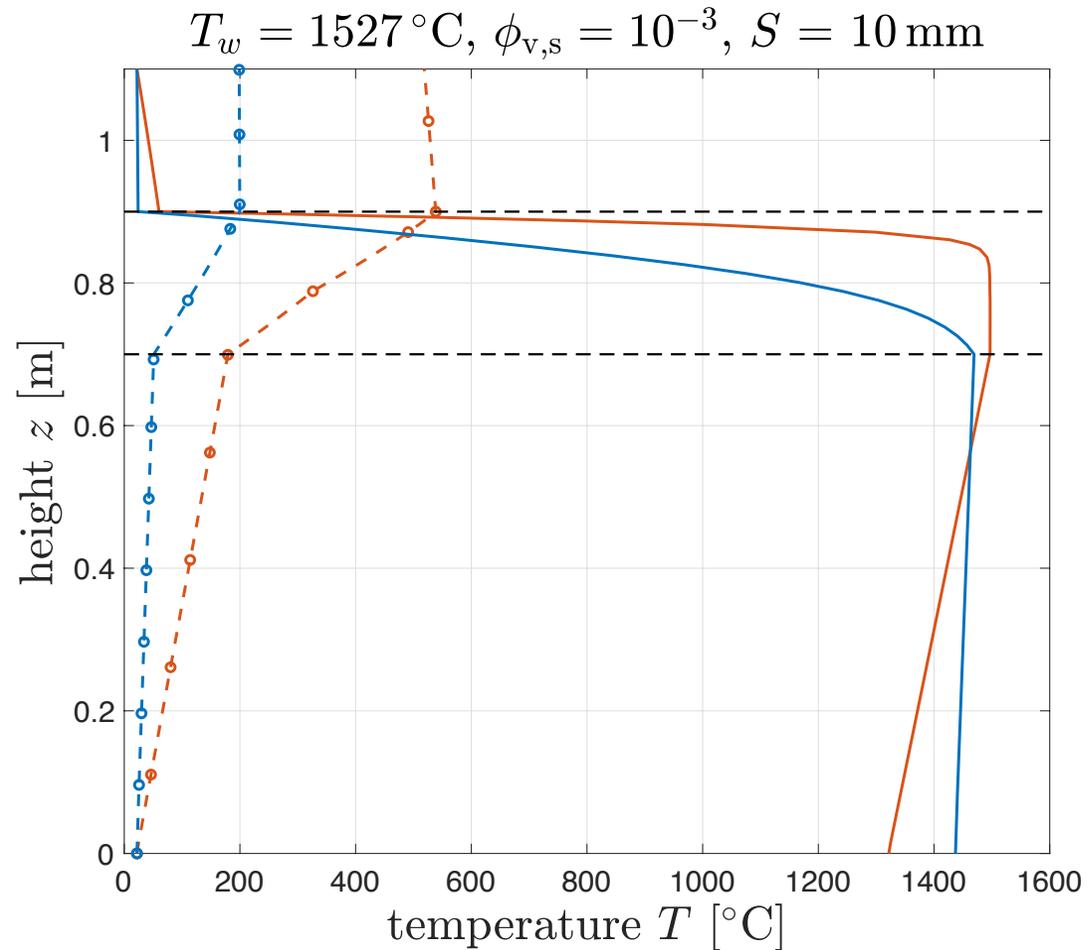
Assumptions:

a. No augmentation by incoming scattering
b. The temperature of the particle is constant along the width/ depth of the duct
c. Each wall acts as a gray emitter
d. Constant absorption & scattering coefficient
e. Only collimated rays emitted by the inner walls
f. Absorption/ scattering coefficient computed for large diffusely reflecting spheres
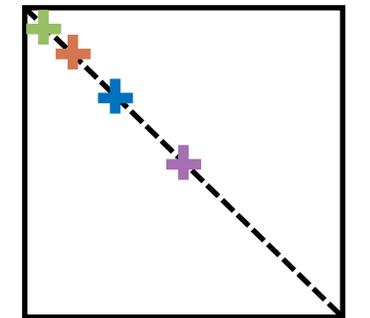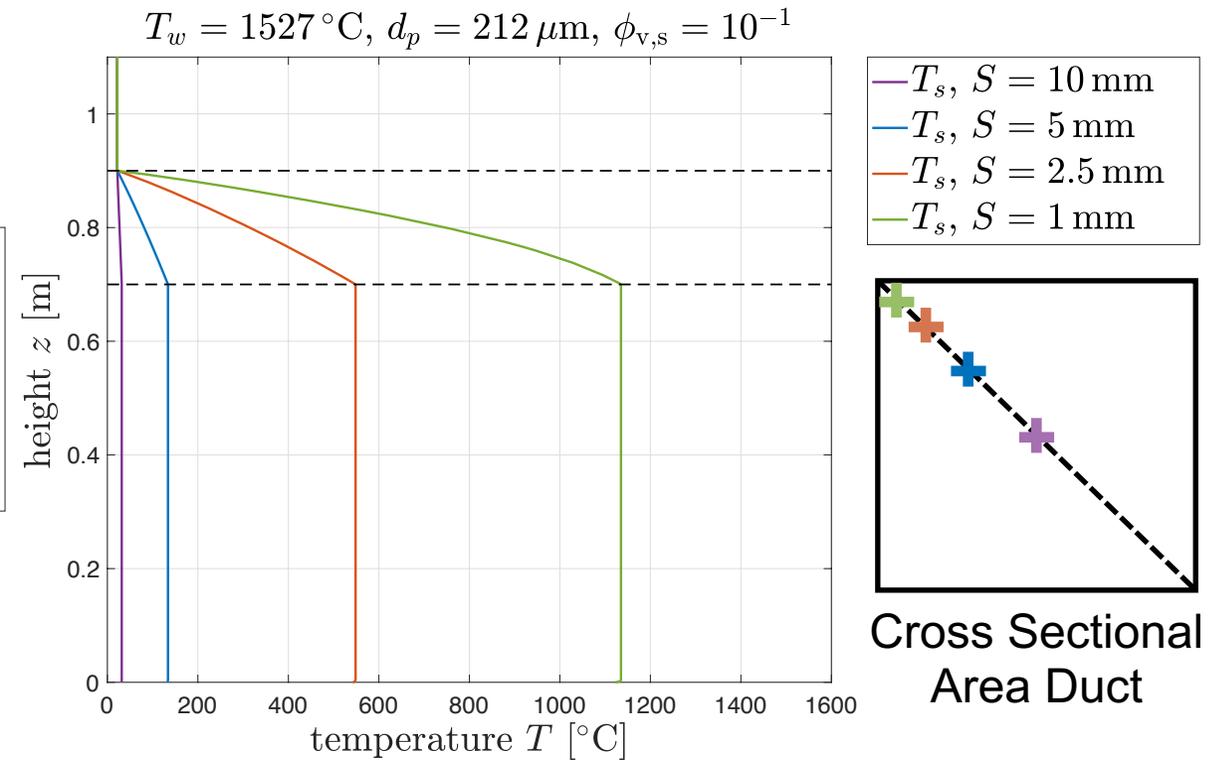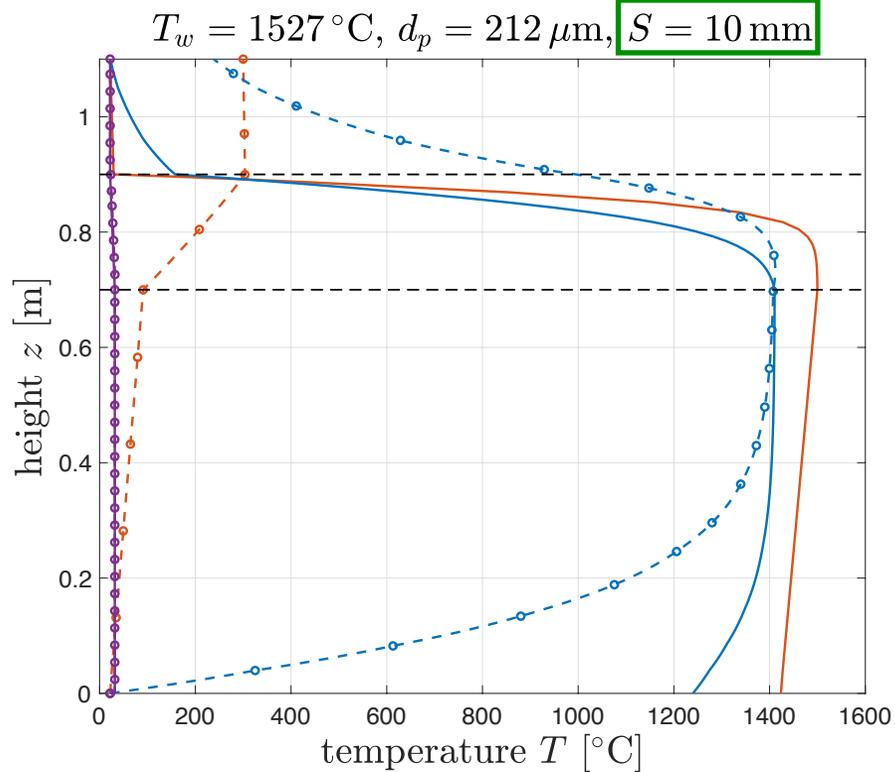
Then, the divergence of the radiative flux of one wall is given by

$$\underline{\nabla}q_{\text{r,one wall}} = 4a \left[\sigma\varepsilon_{\text{s}}T_{\text{s}}(S)^4 - \sigma\varepsilon_{\text{w}}T_{\text{w}}^4\exp(-KS) - \frac{a\sigma\varepsilon_{\text{s}}T_{\text{s}}(S)^4}{K}\{1 - \exp(-KS)\} \right]$$

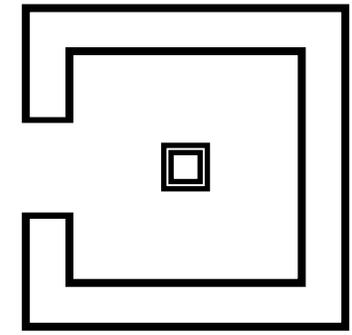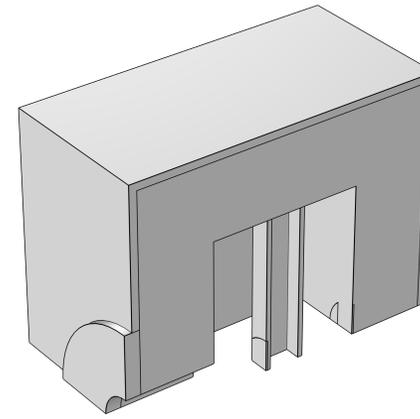Modest, M. F. *Radiative Heat Transfer*, Third Edition, Academic Press, Boston, **2013**

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1D Heat Transfer Model – Results: Influence of Particle Diameter

$T_w = 1527\,°\mathrm{C}, \phi_{\mathrm{v,s}} = 10^{-3}, S = 10\,\mathrm{mm}$

Legend:
- $T_f, d_p = 150\,\mu\mathrm{m}$
- $T_s, d_p = 150\,\mu\mathrm{m}$
- $T_f, d_p = 300\,\mu\mathrm{m}$
- $T_s, d_p = 300\,\mu\mathrm{m}$

x-axis: temperature T [°C]
y-axis: height z [m]
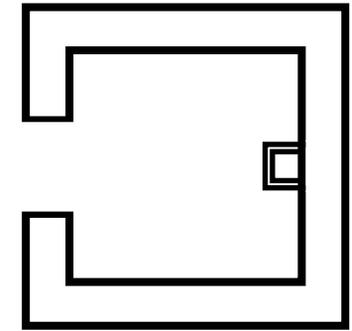
Particles

Air

1D Heat Transfer Model – Results: Influence of Solid Volume Fraction
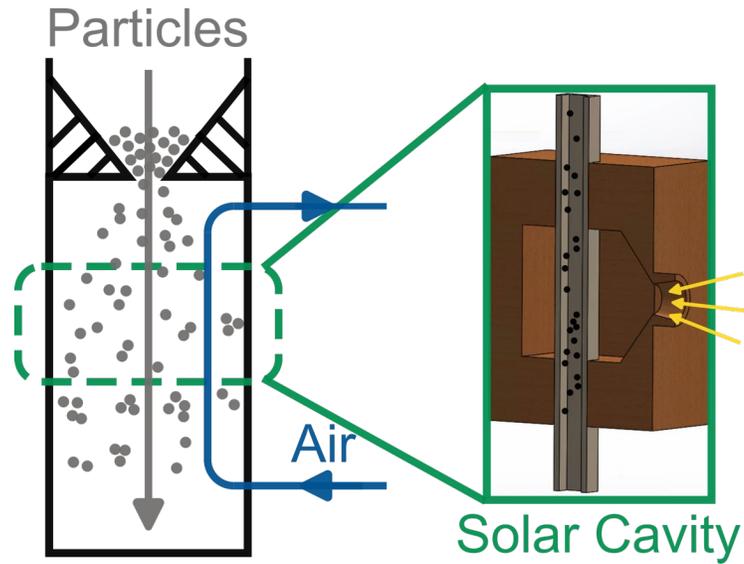
MATLAB version: 9.11.0 (R2021b), Natick, Massachusetts: The MathWorks Inc.; 2023

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Design of Solar Cavity

Particles

Air

Solar Cavity

Configuration A
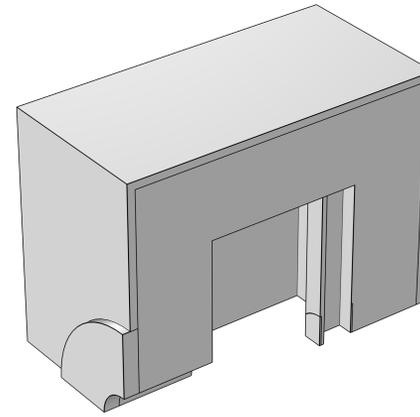
Configuration B
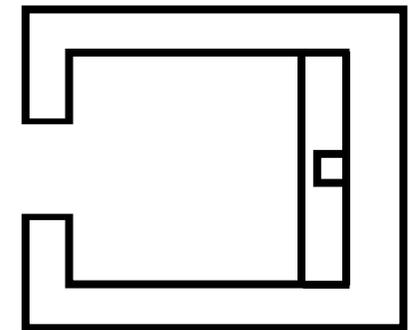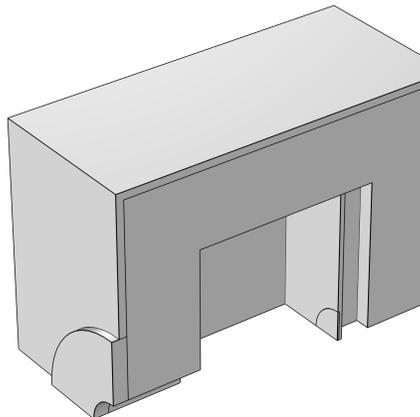
Configuration C

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Design of Solar Cavity – Dimensions of Configurations
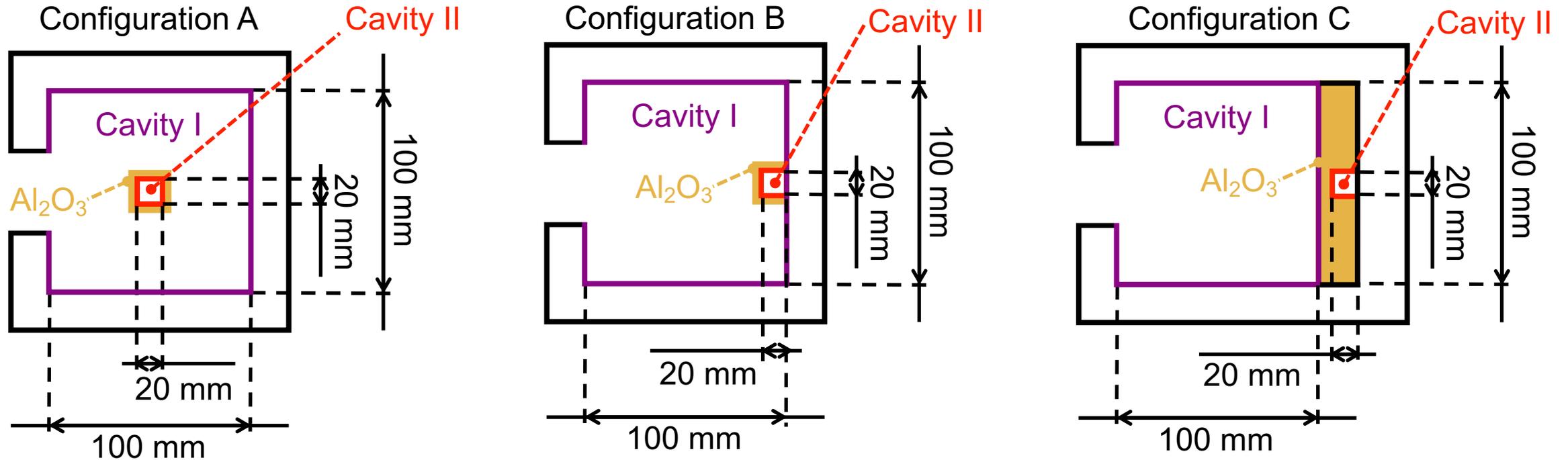
Further, for all configurations:

a. Diameter of Aperture: 40 mm
b. Thickness of Insulation: 50 mm
c. Wall Thickness of Alumina: 3mm
   (except for configuration C – here the thinnest part has a wall thickness of 3 mm)

Simulation Conditions

Radiation Source:

- Collimated Rays
- Direction
- Source heat flux

$$\underline{r} = [x, y, z]^{\mathrm{T}} = [1, 0, 0]^{\mathrm{T}}$$

$$\dot{q}_{\text{solar}} = 1 \cdot 10^{6} \text{Wm}^{-2}$$

It follows:

$$\dot{Q}_{\text{solar}}^{\text{theoretical}} = \dot{q}_{\text{solar}} A_{\text{aperture}} \cong 1256.6 \text{ W}$$

$\longrightarrow$ This is equivalent to a concentration ratio of *C* = 1000 suns
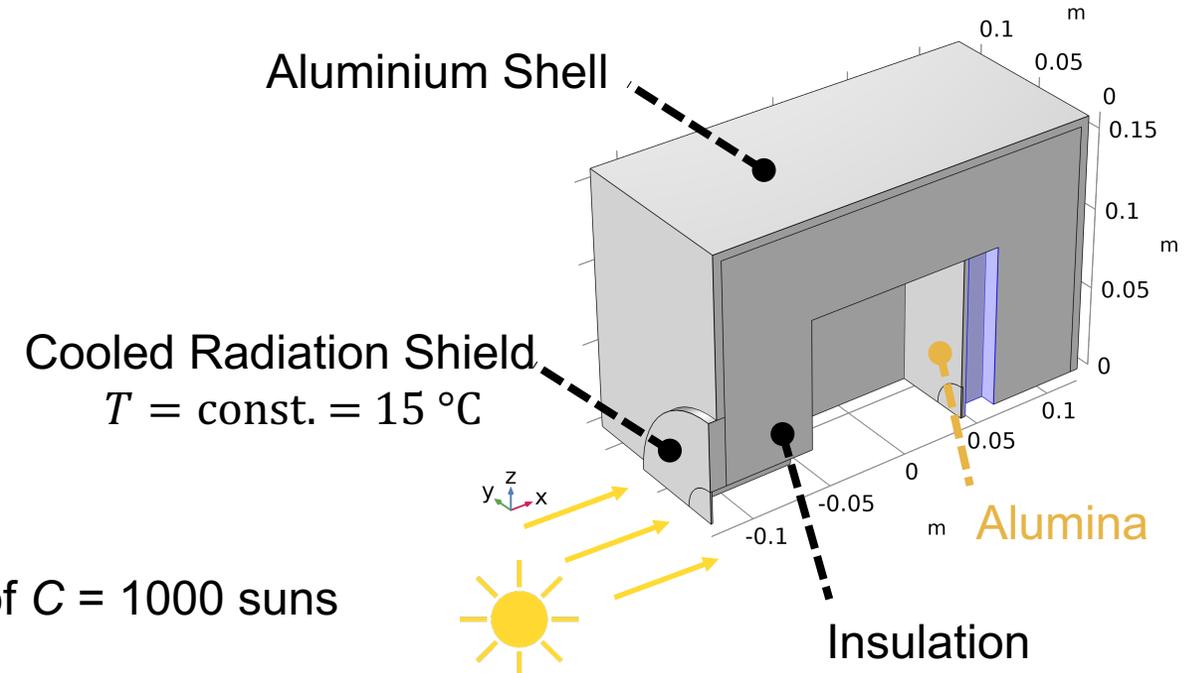
Further:

- Surfaces of aluminium shell radiate heat to the ambient
- Inside the second cavity a convective heat flux is imposed on the surfaces (surfaces highlighted blue)

$$\dot{q}_{\text{sink}} = h_{\text{conv}}[T_{\text{ext}} - T_{\text{w}}] \qquad \text{with} \qquad T_{\text{ext}} = \text{const.} = 20 \,^{\circ}\text{C} \quad \& \quad h_{\text{conv}} = 450 \text{ Wm}^{-2}\text{K}^{-1}$$

- Thermal conductivities of alumina and insulation are assumed to be constant and measured for 1000 °C

$$k_{\text{insulation}} = 0.25 \text{ Wm}^{-1}\text{K}^{-1}$$

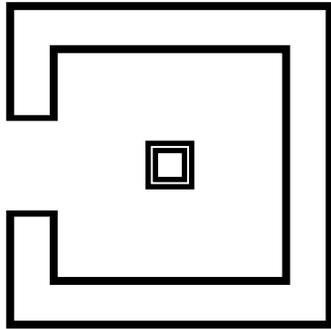$$k_{\text{Al}_2\text{O}_3} = 6.77 \text{ Wm}^{-1}\text{K}^{-1}$$

Aluminium Shell

Cooled Radiation Shield
$T = \text{const.} = 15 \,^{\circ}\text{C}$

Alumina

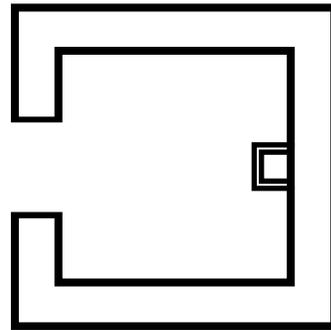Insulation

Estimated Conversion Efficiencies

The three configurations are compared based on the conversion efficiency

$$\eta_{\text{conversion}} = \frac{|\dot{Q}_{\text{sink}}|}{\dot{Q}_{\text{solar}}}$$

Configuration A

Configuration B

Configuration C

$$\eta^{\text{A}}_{\text{conversion}} \cong 49.7\ \%$$

$$\eta^{\text{B}}_{\text{conversion}} \cong 55.0\ \%$$

$$\eta^{\text{C}}_{\text{conversion}} \cong 78.3\ \%$$

COMSOL Multiphysics® v. 5.6. www.comsol.com. COMSOL AB, Stockholm, Sweden

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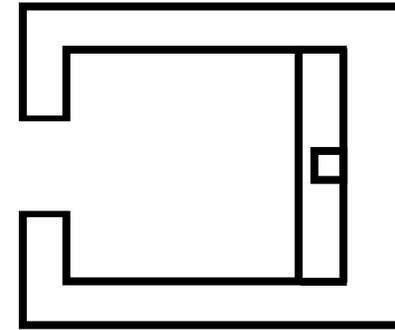
Conclusion

- The 1D heat transfer model captures the most important heat transfer modi, convection and radiation, and estimates temperature profiles which agree with the literature:
    i. Increasing the particle diameter leads to a decrease of the particle temperature
    ii. Increasing the solid volume fraction decreases the particle temperature

- The conversion efficiency is predicted to be highest for configuration C
    ⟶ Building the solar cavity similar to this geometry.

Outlook

- Investigating the hydrodynamics of the counter-current solar particle receiver under room temperature conditions using back lighting and high speed imaging.

- Finalizing the CAD of an experimental facility that will allow to study the thermal performance of the solar particle receiver:
    1. What is the outlet temperature of the particle phase as a function of the particle loading and the velocity of the counter-current air flow?
    2. What is the overall heat transfer coefficient?

- Assessing if the cluster formation has an effect on the heat transfer performance of the receiver.