The influence of radiative transfer on the turbulent flow inside solar absorbers operating with supercritical CO_2

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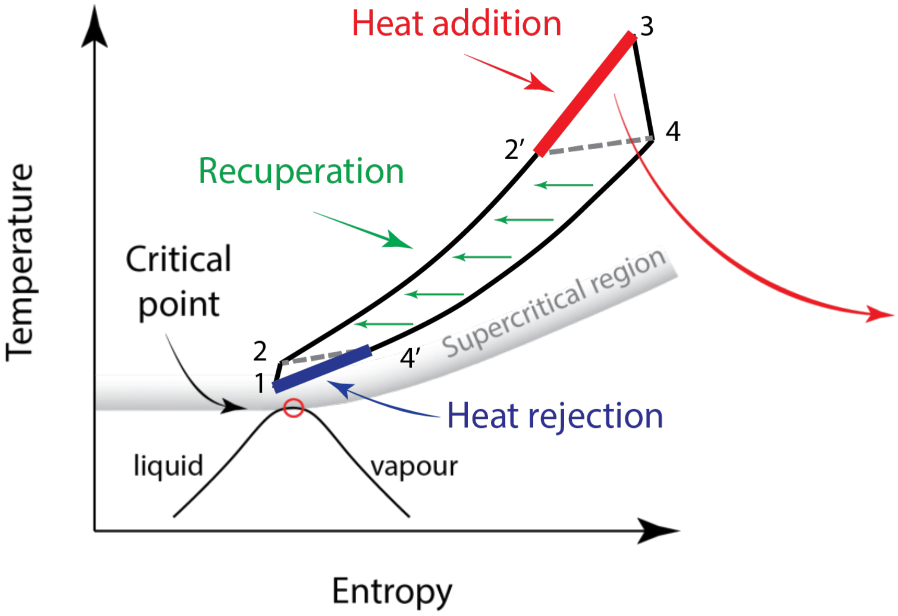
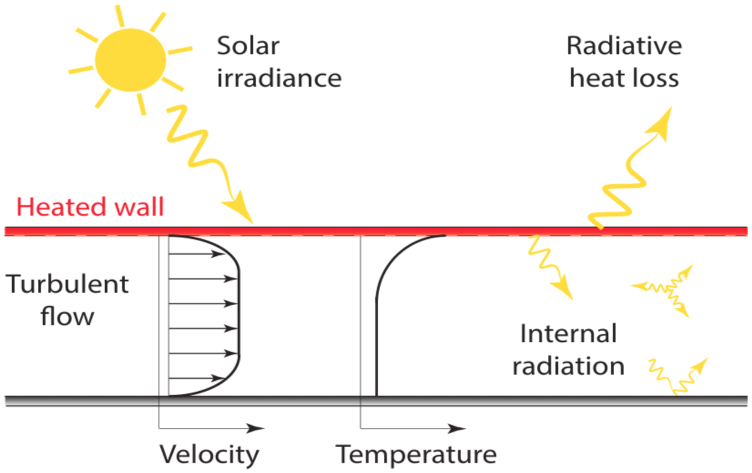
Contents

- Surface vs. volumetric receivers
- Optical properties of $scCO_2$ and nanoparticles
- Numerical methods
- Investigated cases
- Results
- Conclusions and recommendations

Solar receivers for scCO2 cycle



Surface receiver



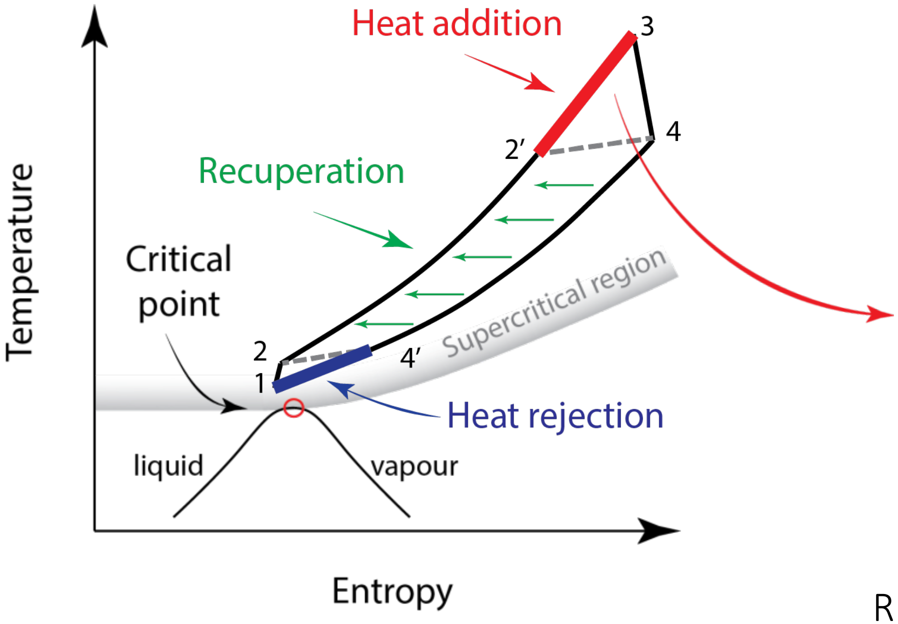
Selective coating at the surface

- High absorptance for solar band
- Low emittance for infrared band

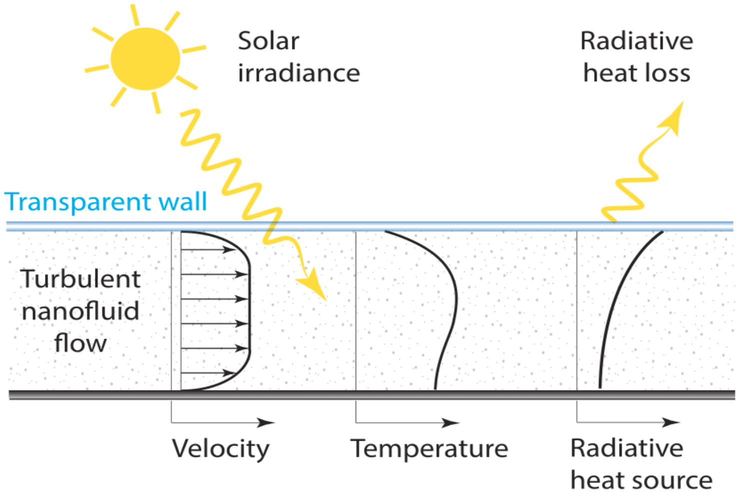
High wall temperatures

- Radiation inside the receiver
- Relatively large emissive losses
- Low efficiency

Solar receivers for scCO2 cycle



Volume receiver



Radiation absorbed by nanoparticles (1 – 100 nm)
Optimize absorption with volume fraction & material

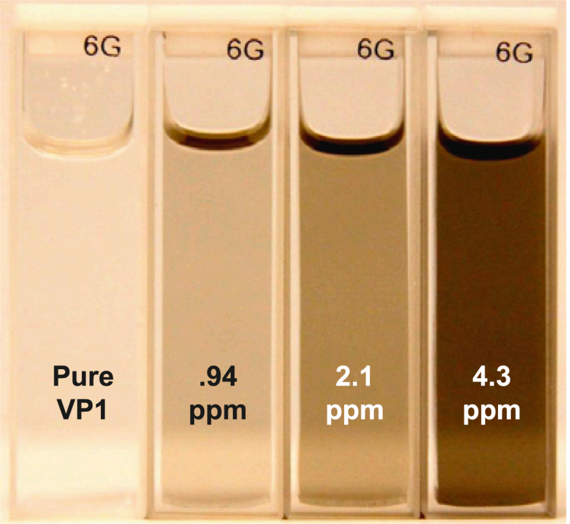
Nanoparticles:

- no significant sedimentation velocity
- no significant erosion to the equipment
- do not readily deposit on walls

Nanofluids for solar thermal receivers

Nanofluids solar thermal receivers:

- Hordy et al., Solar Energy, 2014
  - Metal- and carbon based nanoparticles in water and VP1
  - Thermal stability tests up to 220 °C (VP1 boiling temp. 257 °C)
- Metallic nanoparticles:
  - Plasmonic effect



Carbon coated cobalt nanoparticle in VP1
Lenert et al., Solar Energy, 2012

scCO2 used for nanoparticle synthesis (RESS) and mixing:

  - G.P. Sanganwar, R.B. Gupta, Powder Technology, 196(1) (2009) 36-49.
  - M. Carrott, C. Wai, Analytical chemistry, 70(11) (1998) 2421-2425.

Research questions

1. **How does radiation within surface receiver affect performance?**

2. **What is the theoretical potential of volumetric receivers?**
    - Comparison surface and volumetric receivers with $scCO_2$

Optical properties

- $scCO_2$
- Nanoparticles
- Nanofluid (scCO$_2$ + nanoparticles)

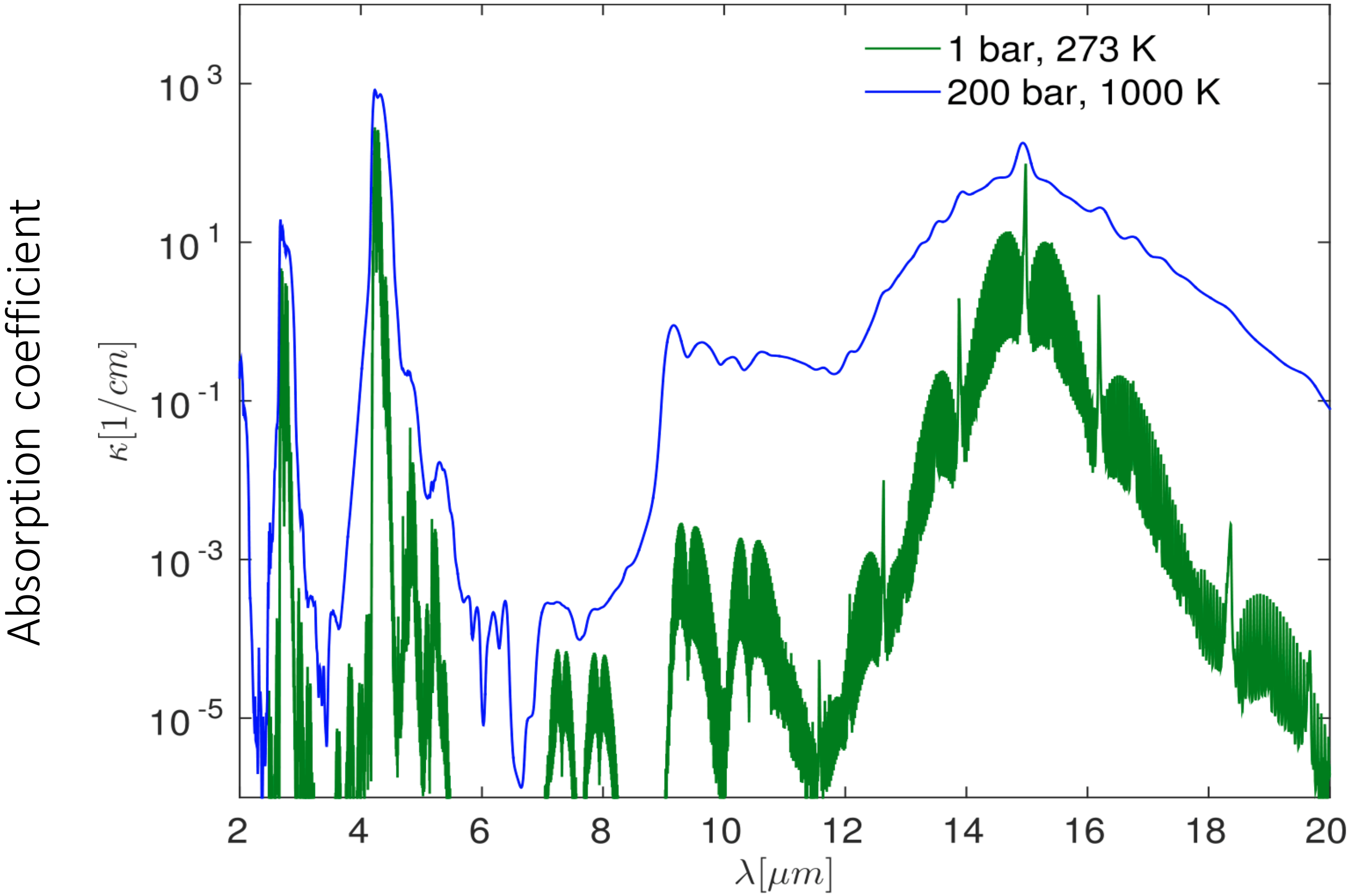
Optical properties of $scCO_2$

- HITRAN database → spectral lines
- Lorentz broadening of spectral lines
- Sub-Lorentzian behaviour
  - Deviation of Lorentz shape (Perrin & Hartmann, 1989)
  - Extrapolation of empirical relations
- Open-source software to obtain k-spectrum

<u>Refs:</u>

- Rothman et al., 2013. J. of Quantitative Spectroscopy and Radiative Transfer, 130, 4–50.
- Rosenmann, el at., 1988. Applied Optics, 27(18), 3902–3907.

Optical properties of s-CO2



Optical properties of particles

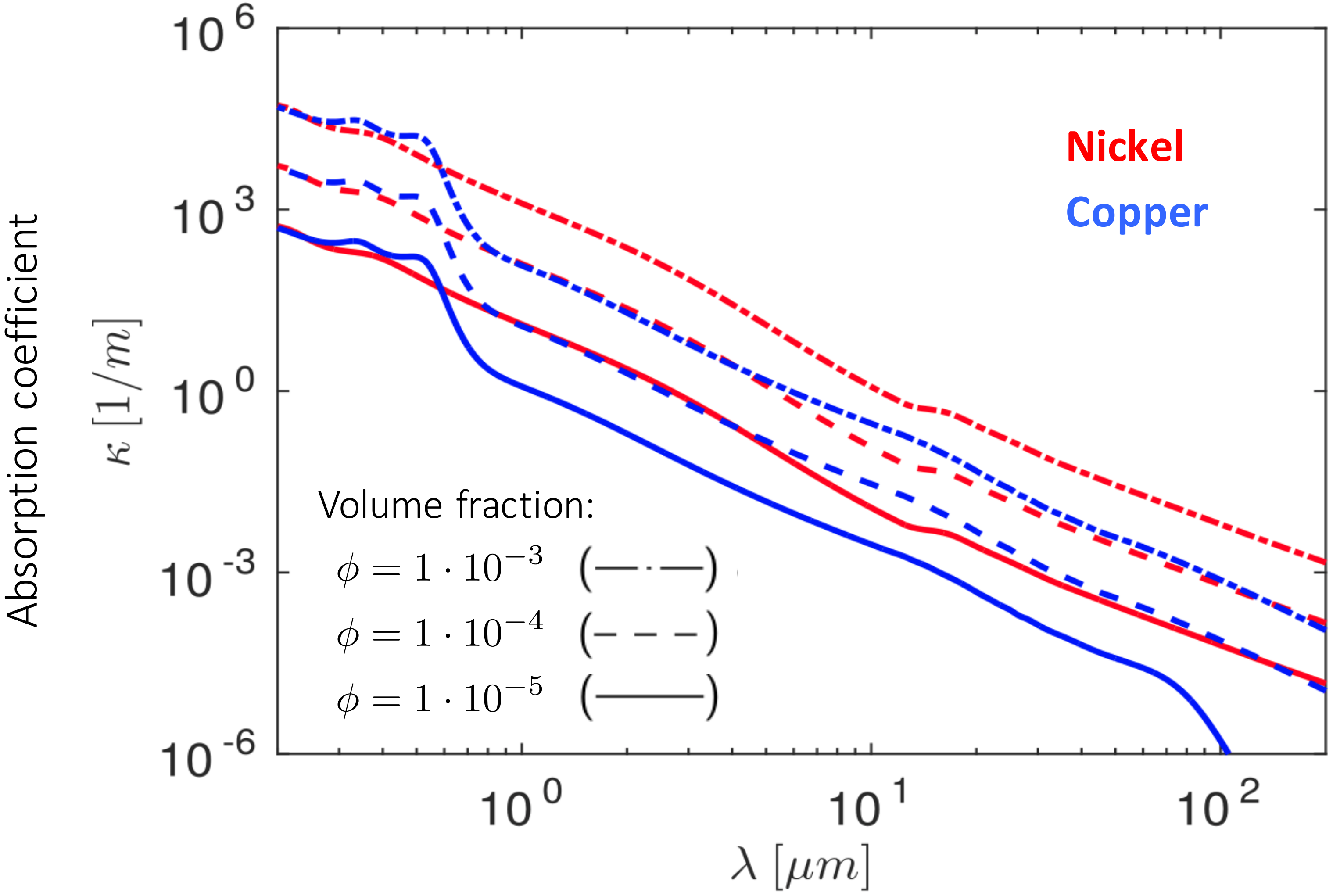
- Two materials chosen with high melting temperatures
  - Nickel and Copper

- Rayleigh scattering theory (Modest, 2012)
  - Very small particles compared to wavelength
  - Transparent medium with particles
  - Low volume fraction

$$\kappa_\lambda = -\Im\left(\frac{m^2-1}{m^2+2}\right)\frac{6\pi\phi}{\lambda}.$$

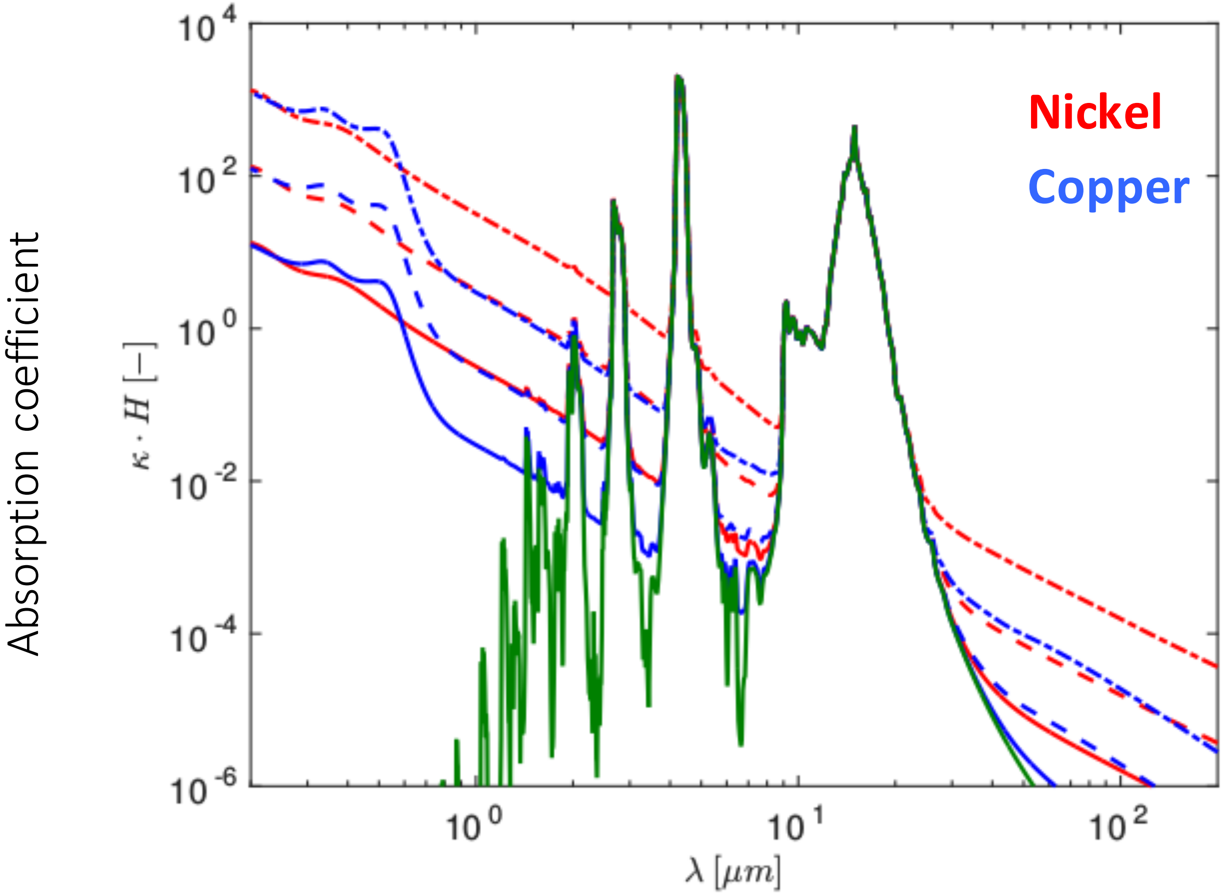
- Complex index of refraction from literature
  - Ordal et al. (1985), Rakic et al (1998)

Optical properties of particles



Optical properties of particles

- Linear combination of absorption spectra: $\kappa_{nf} = \kappa_p + \kappa_f$



Volume fraction:

$\phi = 1 \cdot 10^{-3}$ (—·—)

$\phi = 1 \cdot 10^{-4}$ (– – –)

$\phi = 1 \cdot 10^{-5}$ (——)

Numerical method

Navier-Stokes solver
Radiative transfer solver

Numerical method

- Favre averaged Navier-Stokes equations (enthalpy based)

$$\frac{\partial \overline{\rho}\widetilde{u}_i}{\partial x_j} = 0,$$

$$\frac{\partial \overline{\rho}\widetilde{u}_i\widetilde{u}_j}{\partial x_j} = \frac{\partial \overline{p}_i}{\partial x_i} + \frac{1}{Re_0}\frac{\partial \overline{\tau}_{ij}}{\partial x_j},$$

$$\frac{\partial \overline{\rho}\widetilde{h}\widetilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\overline{\alpha}}{Re_0 Pr_0} + \frac{\mu_t}{Pr_t}\right)\frac{\partial \widetilde{h}}{\partial x_j}\right] - R\frac{\partial q_r}{\partial x_j},$$

- Radiative heat source:

$$\frac{\partial q_r}{\partial x_j} = \int_0^\infty \kappa_\lambda \left(4\pi I_{b\lambda} - \int_{4\pi} I_\lambda d\Omega\right) d\lambda,$$

- Radiative transfer equation:

$$\int_0^\infty \frac{dI_\lambda}{ds} d\lambda = \int_0^\infty \kappa_\lambda (I_{b\lambda} - I_\lambda) d\lambda$$

Governing equations

Inhouse RANS and radiative transfer solver:

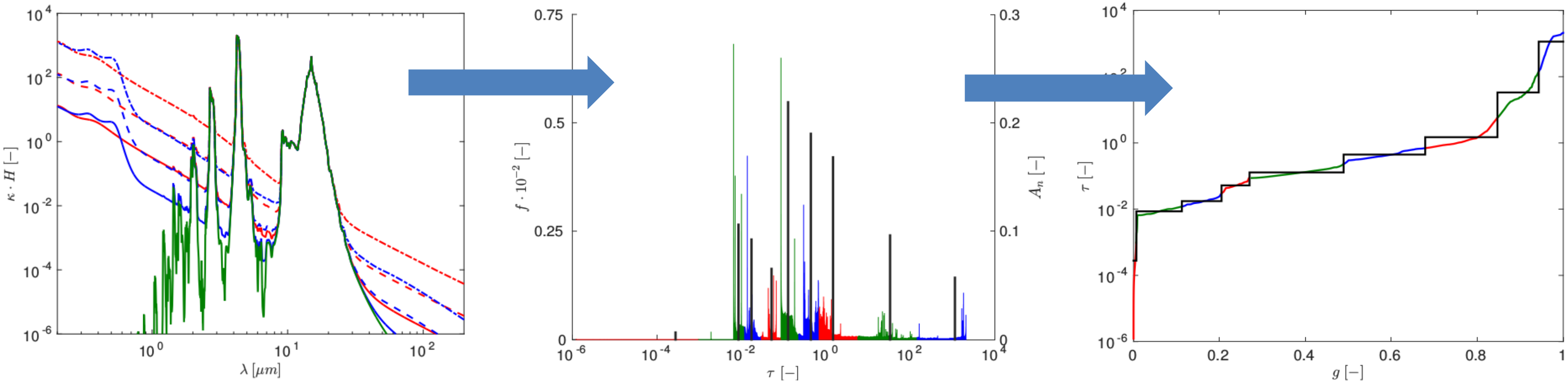
- Incompressible 2D RANS solver
    - Variable transport properties (NIST, Span & Wagner, 2004)
    - Finite volume method
    - SIMPLE solver

- k-ε turbulence model
    - Myong & Kasagi, 1990

- Radiation model
    - Finite volume method
    - Weighted sum of gray gases

Radiation modeling

- Full k-distribution model (Modest, 2002)
  - Method for reducing number of equations for radiation
  - Convert absorption spectra from wavelength domain to g-space domain using k-distributions
  - Wavelengths with the same absorption coefficient are matched
  - Distributions are more smooth, therefore more suitable to fit
- Weighted Sum of Grey Gasses (WSGG) model
  - Approximation of k-distribution model (Modest, 2002)



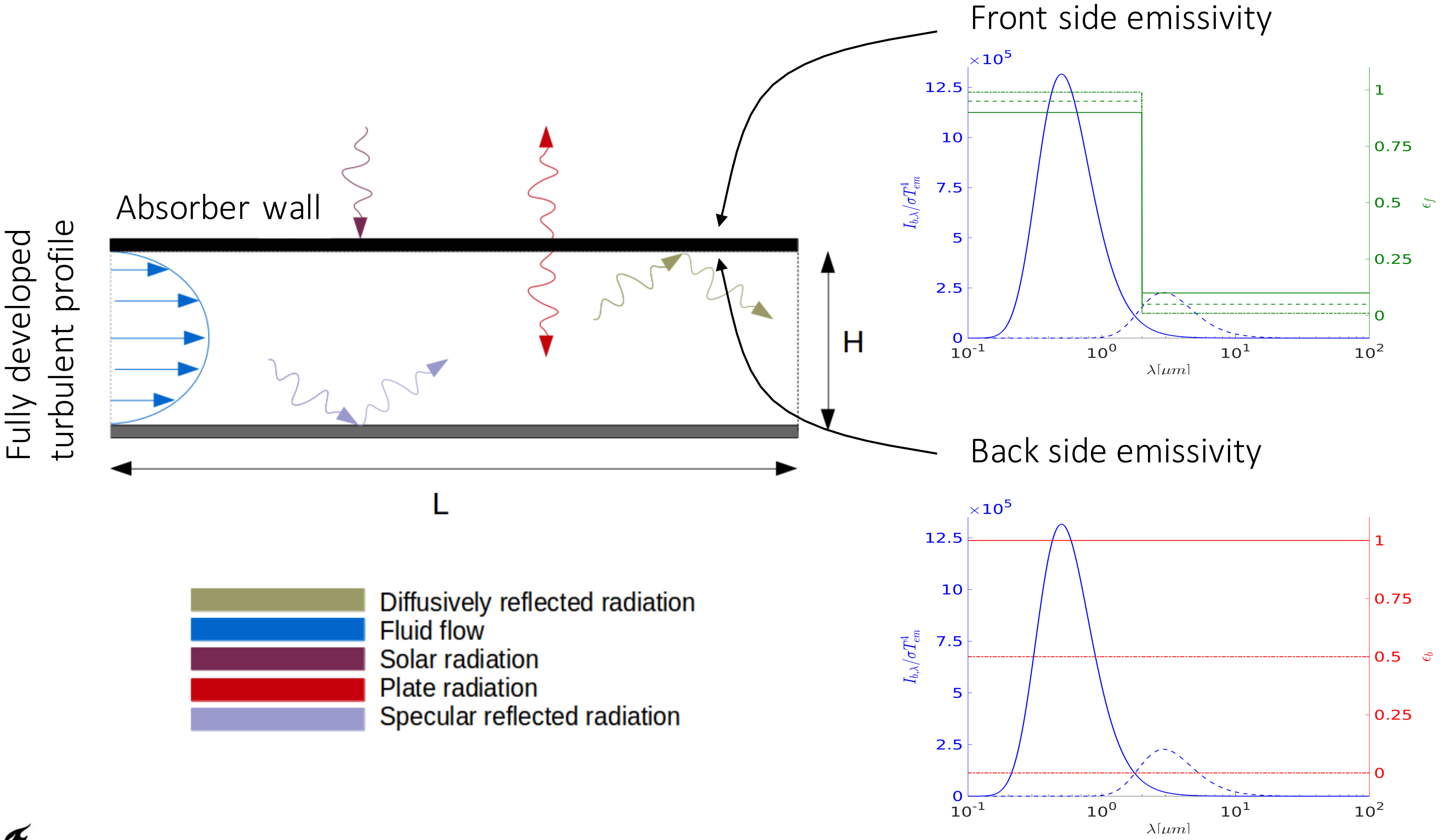
Absorption spectrum

k-distributions

g-space domain

Boundary conditions

Boundary conditions: surface receiver

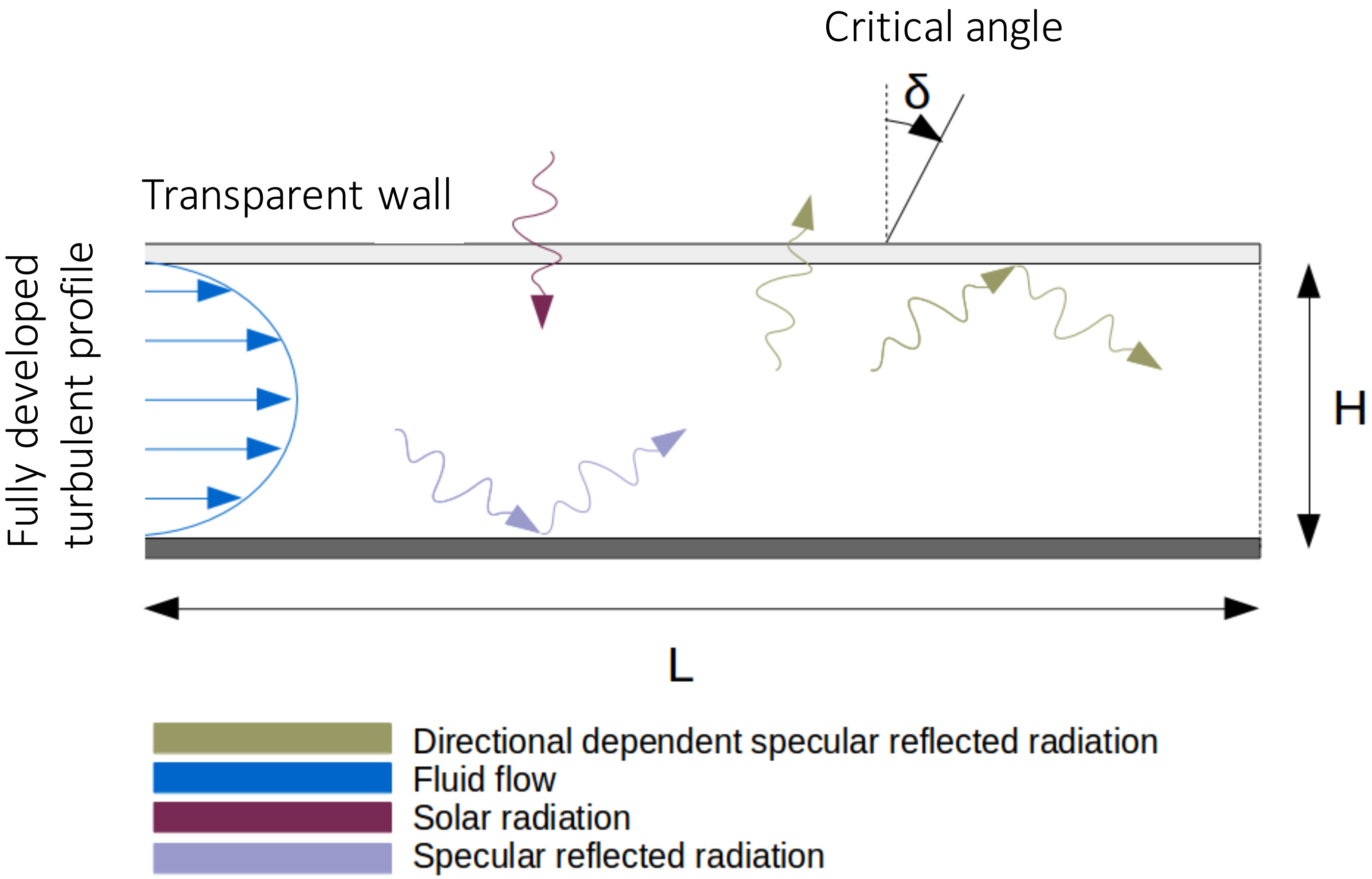


Front side emissivity

Back side emissivity

- Diffusively reflected radiation
- Fluid flow
- Solar radiation
- Plate radiation
- Specular reflected radiation

Boundary conditions: volumetric receiver

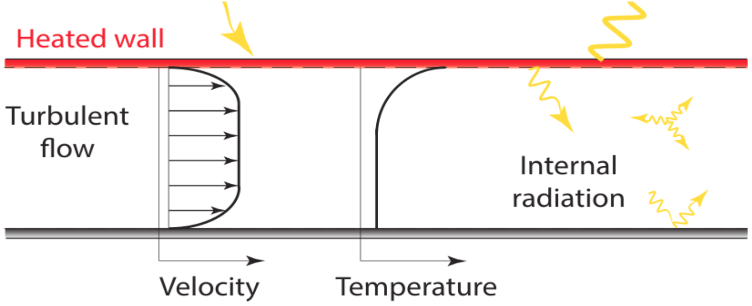


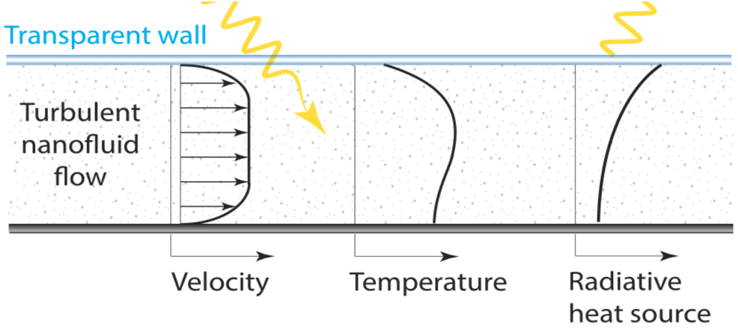
Investigated parameter space

Overall boundary conditions	
Receiver inlet temperature	550 °C
Operating pressure	200 bar
Receiver length & height	4 m x 2.5 cm
Reynolds number	7000
Solar concentration factor	25 / 50 / 75

Surface receiver	
Front side emissivity	0.9 / 0.95 / 0.99
Back side emissivity	0.0 / 0.5 / 1.0

Volumetric receiver	
Volume fraction	10^{-3} / 10^{-4} / 10^{-5}
Critical angle	30° / 50° / 70°

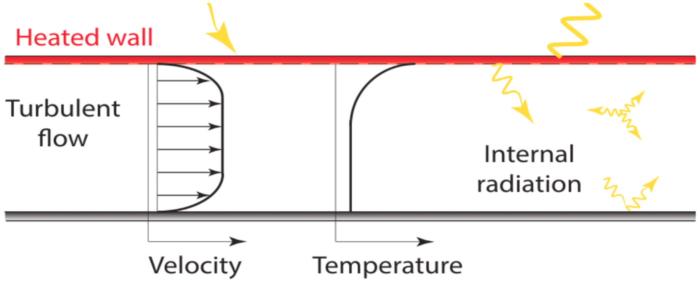




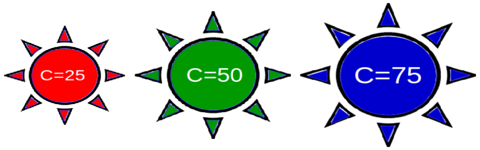
Results

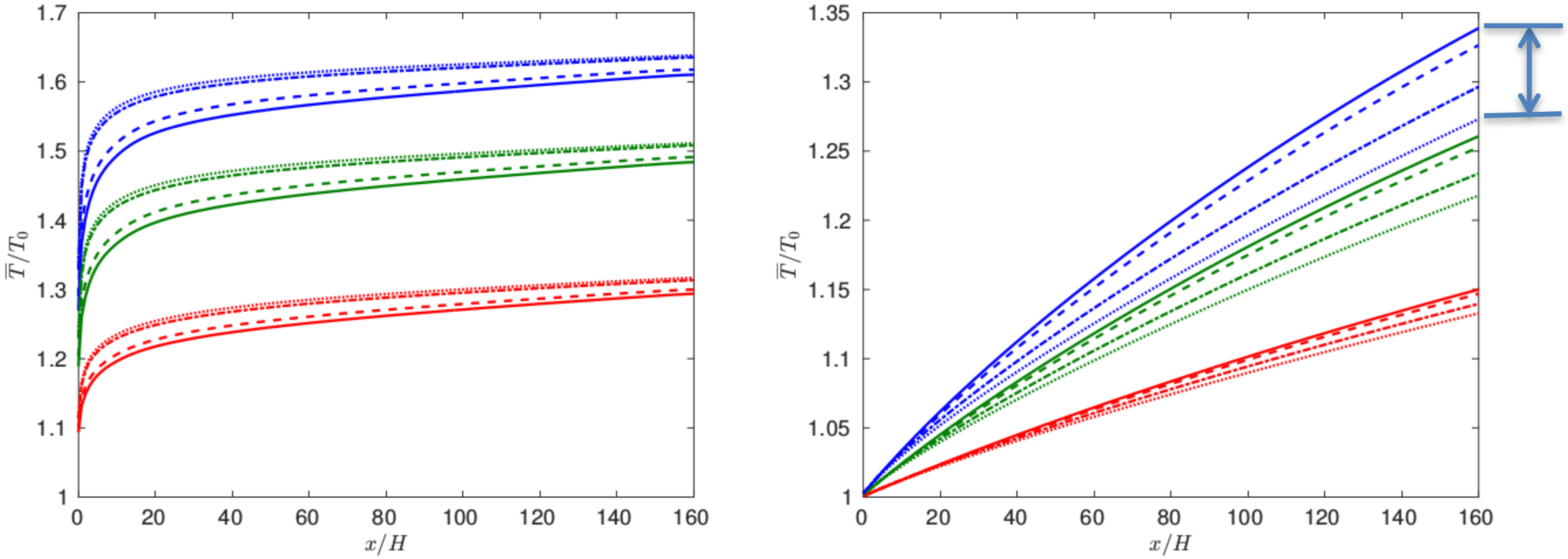
- Surface receiver
- Volumetric receiver

Surface receiver: varying back side emissivity



(——) $\epsilon_b = 1$
(- - -) $\epsilon_b = 0.5$
(—-—) $\epsilon_b = 0.0$
(··········) no radiative heat transfer



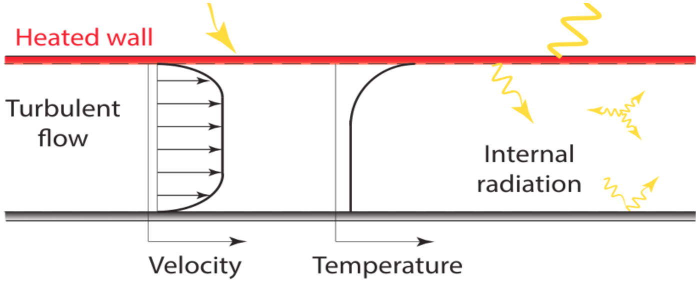


(a) Receiver plate temperature

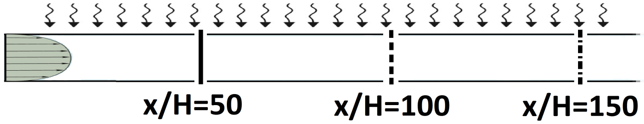
(b) Bulk temperature

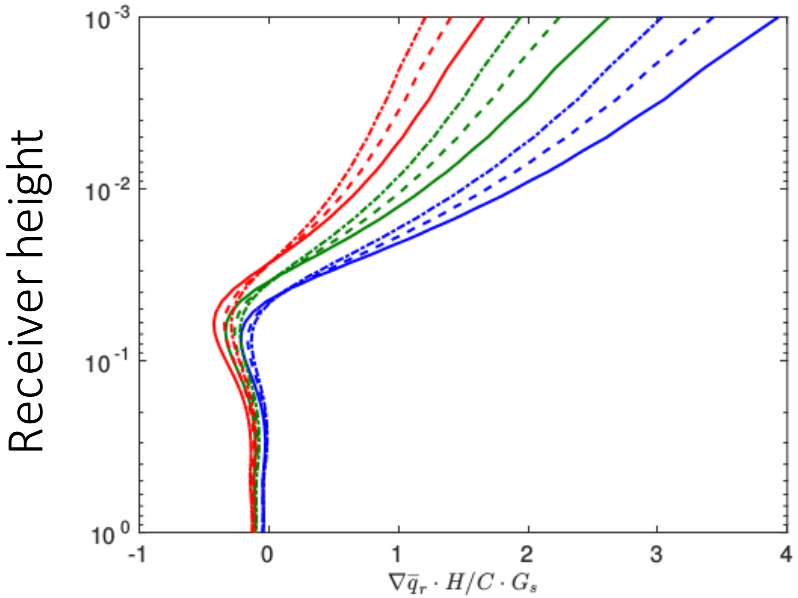
8% higher with radiation

Surface receiver: varying back side emissivity



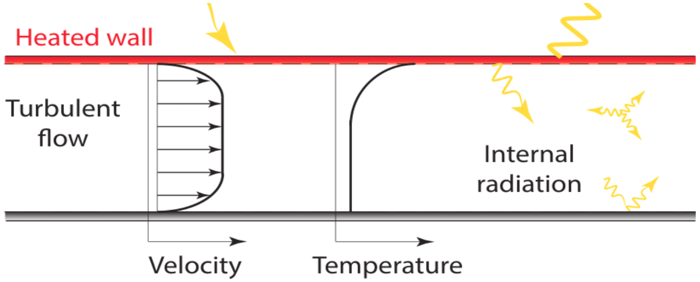
[C=75, $\epsilon_f = 0.9$]





(a) Volumetric heat source

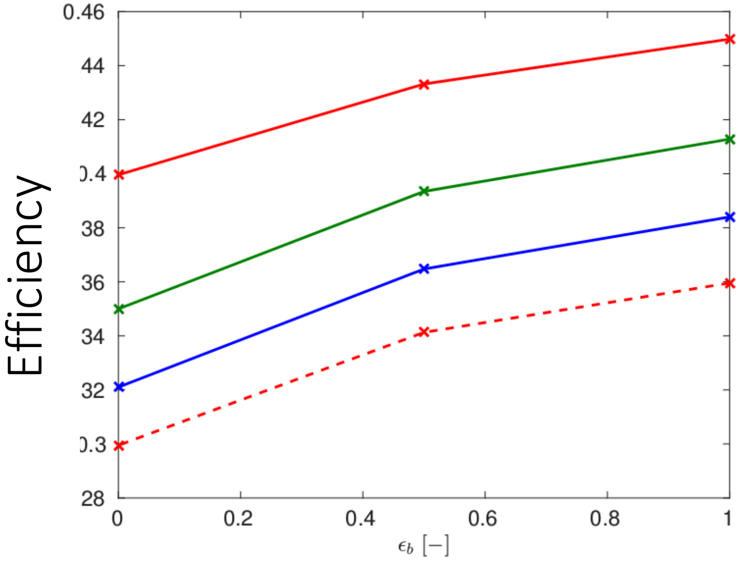
Surface receiver: performance



[C=75, $\epsilon_f = 0.9$]

Efficiency definition:

$$\eta_{rec,x} = \frac{\dot{m}(h_x - h_{in})}{q_s A_{rec,x}}$$

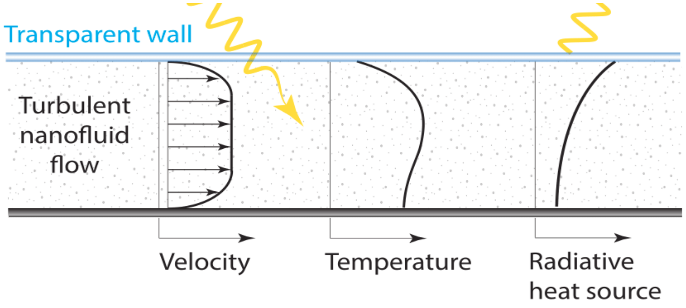


(a) Efficiency as a function of receiver plate back side emissivity [$\epsilon_{f,1} = 0.9$]

Desired receiver outlet temperature:

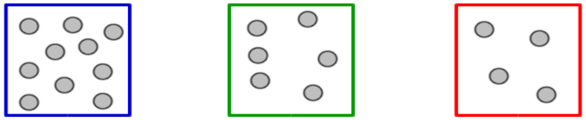
- 600 [°C]
- 650 [°C]
- 700 [°C]
- 750 [°C]

Volumetric receiver: varying volume fraction

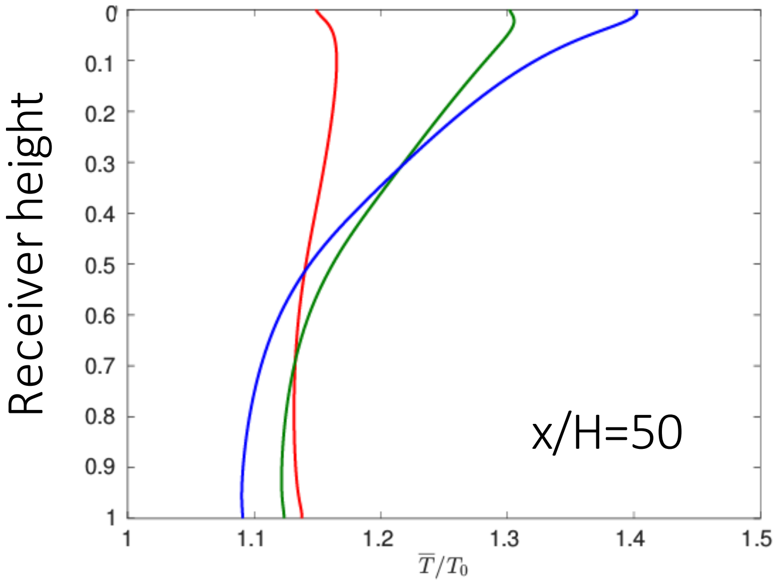


$$[C = 75,\ \delta_c = 70°]$$

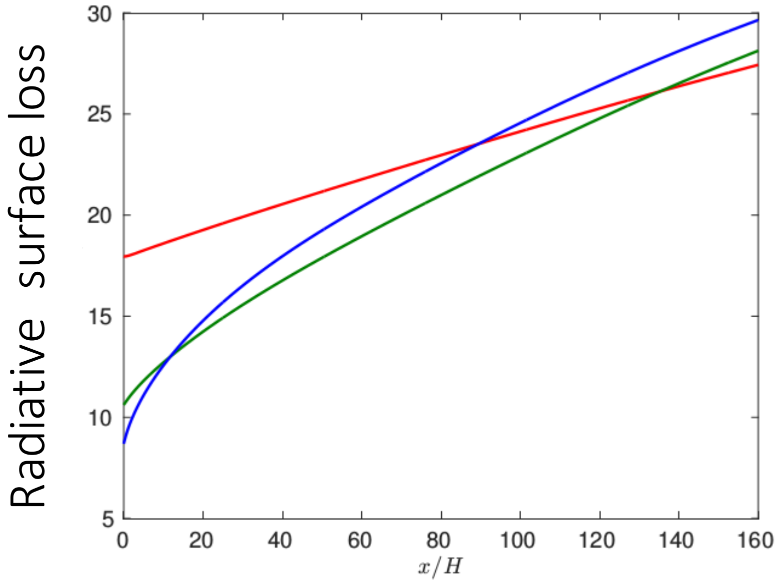
Volume fraction:



$\phi = 1 \cdot 10^{-4}$ (blue), $\phi = 4 \cdot 10^{-5}$ (green), $\phi = 1 \cdot 10^{-5}$ (red)

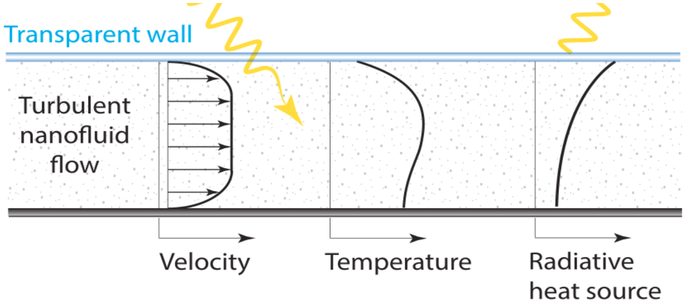


(a) Transverse contour lines of temperature:



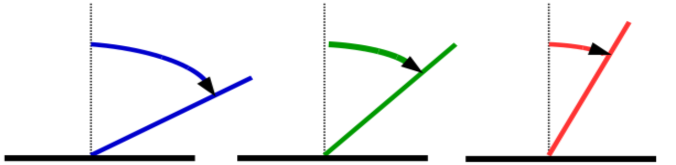
(b) Surface losses

Volumetric receiver: varying critical angle

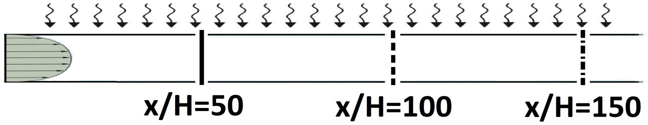


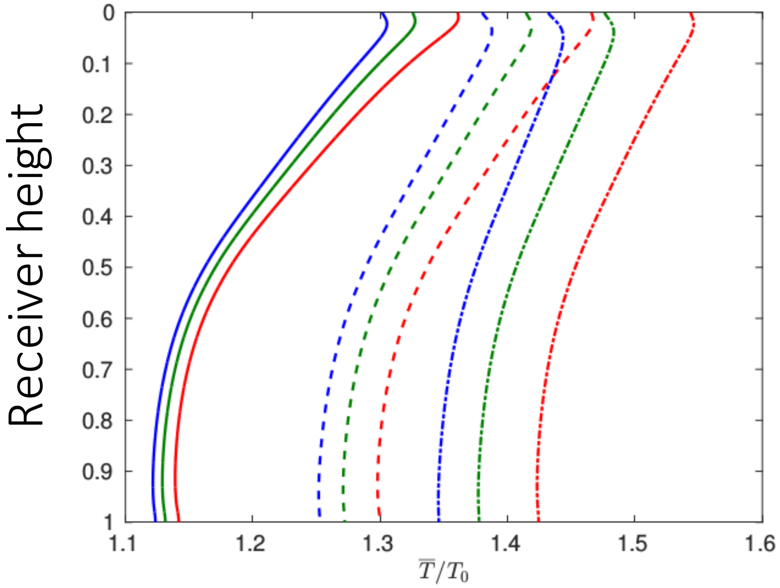
$$[C = 75,\ \phi = 4 \cdot 10^{-5}]$$

Critical angle:

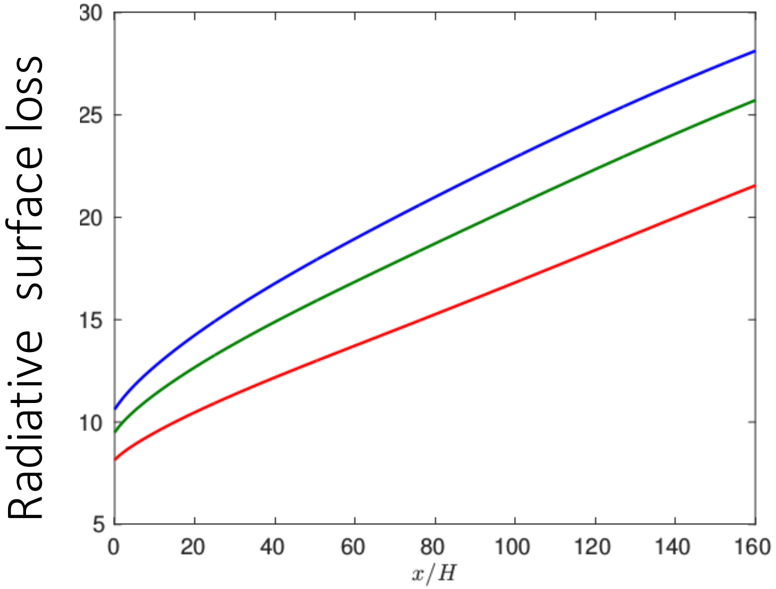


$\delta_c = 70°$ (blue), $\delta_c = 50°$ (green), $\delta_c = 30°$ (red)



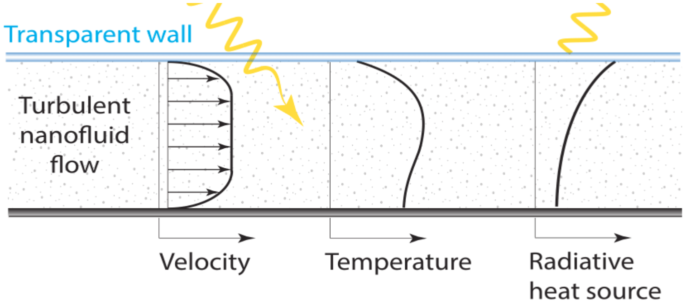


(a) Transverse contour lines of temperature:

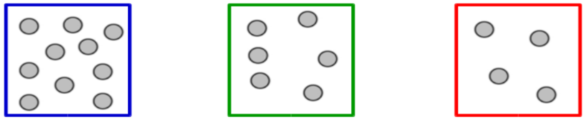


(b) Surface losses

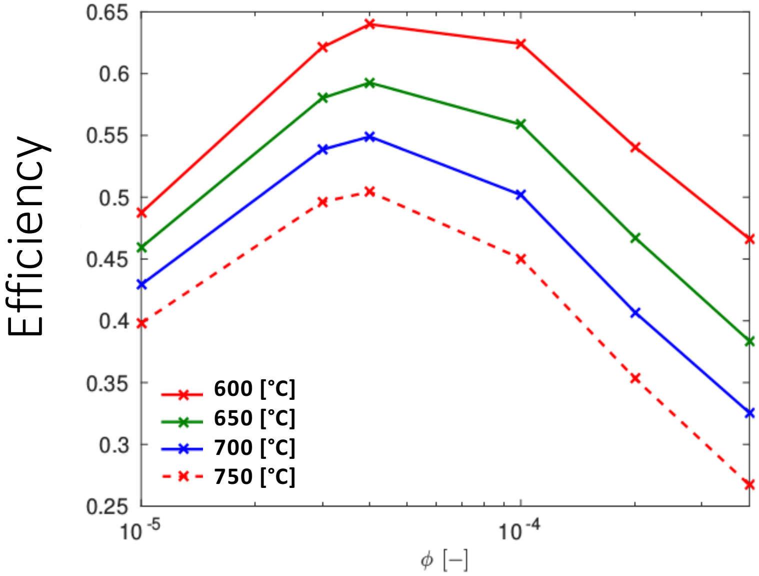
Volumetric receiver: performance



Volume fraction:

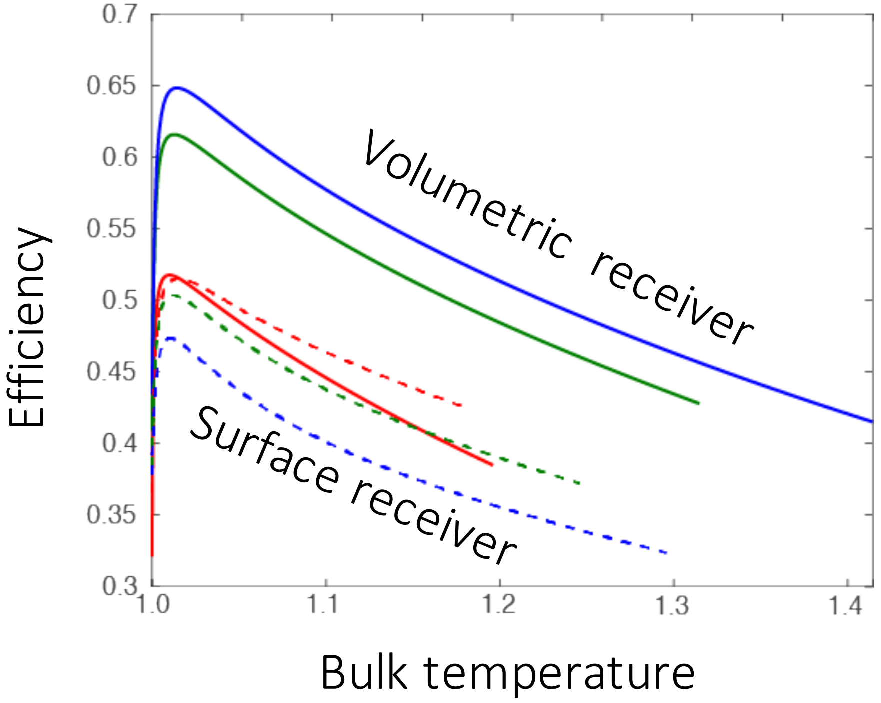


$\phi = 1 \cdot 10^{-4}$ (blue), $\phi = 4 \cdot 10^{-5}$ (green), $\phi = 1 \cdot 10^{-5}$ (red)



(a) Efficiency as a function of volume fraction $[\delta_c = 70°]$

Performance comparison



Solar concentration: C=25 C=50 C=75

Conclusions

- Absorption peaks for CO_2 at 200 substantially broaden

- Radiative transfer has to be taken into account in surface receivers
    - efficiency 8% higher with radiation

- Substantial higher efficiencies for volumetric receivers for high solar concentration factors
    - Low radiative losses for volumetric receiver -> low surface temperature
    - Radiative losses limited to a thin layer close to the transparent surface

Recommendations

- Turbulent radiation interaction for optically thick media is unknown
- Experiments are crucial to prove concept with nanoparticles in $scCO_2$
    - Nanoparticle agglomeration and thermal/chemical stability, etc.
- Volumetric receiver design challenging for high pressures