Calculation of radiative losses of solar receivers using viewfactors

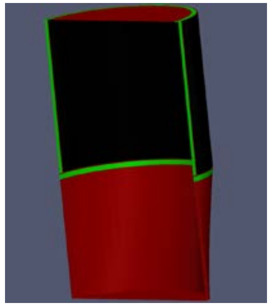
OpenFOAM user conference 2014

Institute of Solar Research, German Aerospace Center
Fabian Frie

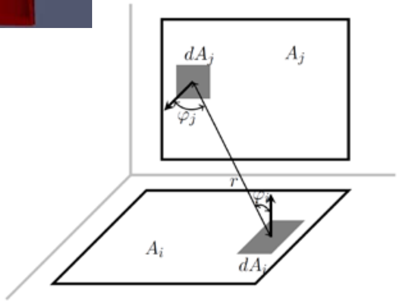
DLR

Content

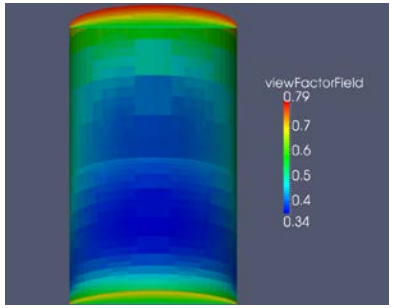
1) Introduction to CSP
and Solar Receivers



2) Simulation Setup & Boundary Conditions



3) Radiation Model – Viewfactor

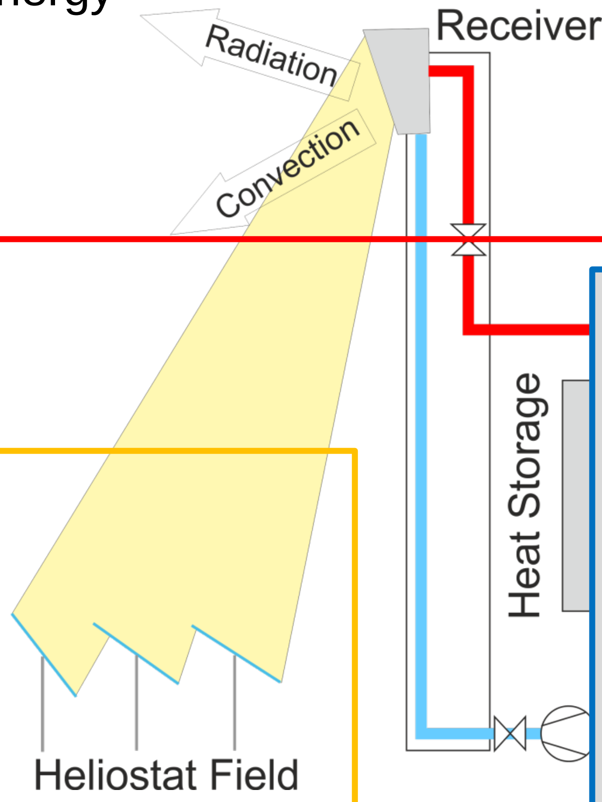


4) Results and Summary

Working principle of solar power towers

Transforming radiation into thermal energy

Concentrated solar radiation



- Thermochemical cycles
- Solar methane reforming
- Solar high-temperature electrolysis

Receiver technologies

- **Convex or concave receiver types**
- Absorber: black pipes heating either molten salt or directly vaporizing water
- **Closed process**

Open volumetric receiver

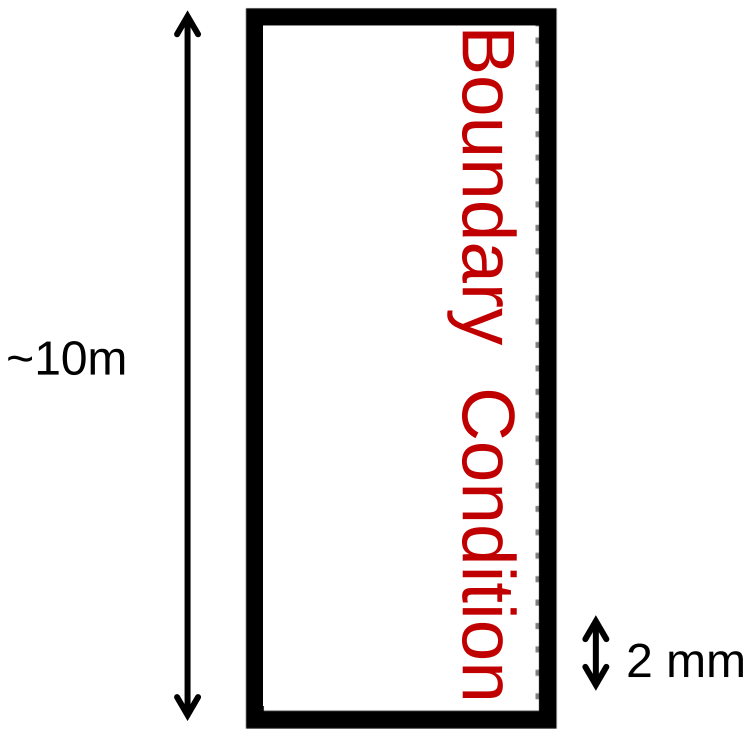
- Absorber: black porous ceramic structure (honeycomb)

- Ambient air is drawn through the channels and heats up to 800°C – 1000°C

  → **Open process**

Modelling an open volumetric cavity receiver

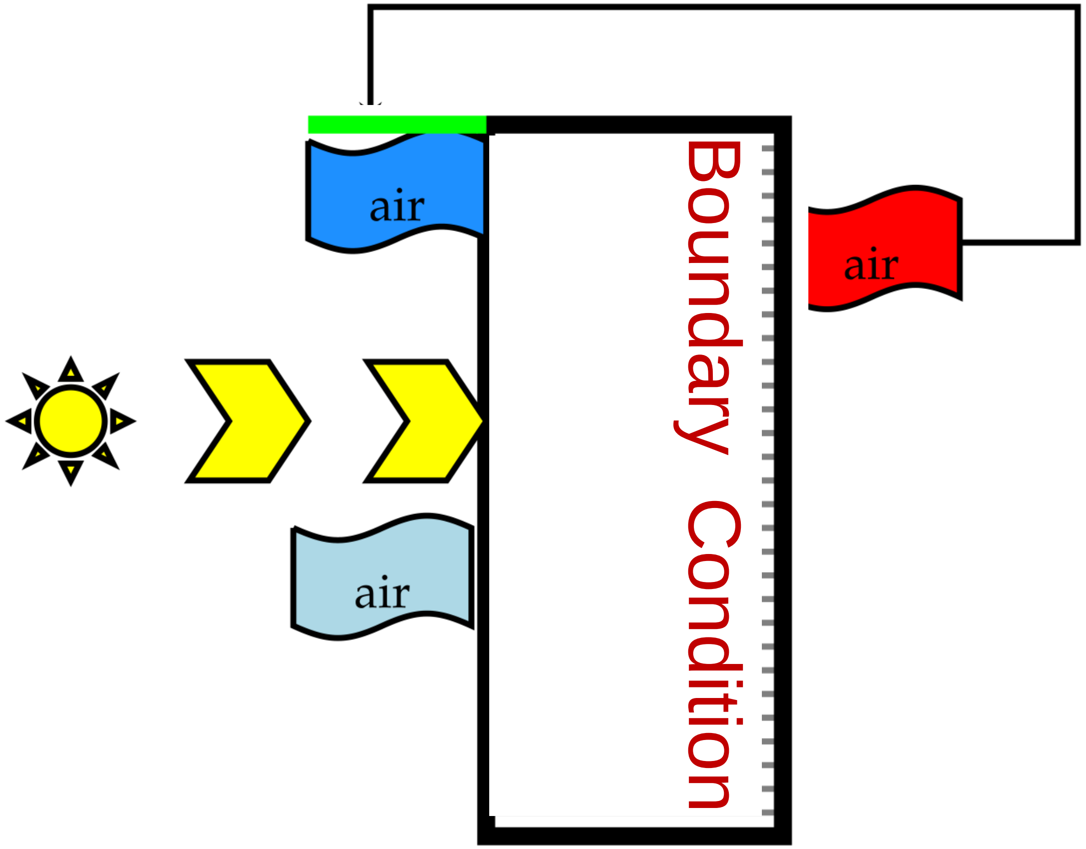
- **Key features:**
- Porous absorber structure has a very small length scale
  → absorber behavior as BC
  → **wall** for radiation model
  → **outlet** for fluid simulation



Modelling an open volumetric cavity receiver

- **Key features:**
- Porous absorber structure has a very small length scale
  → absorber behavior as BC
  → **wall** for radiation model
  → **outlet** for fluid simulation

- Heliostat field included as **source term** for radiation model

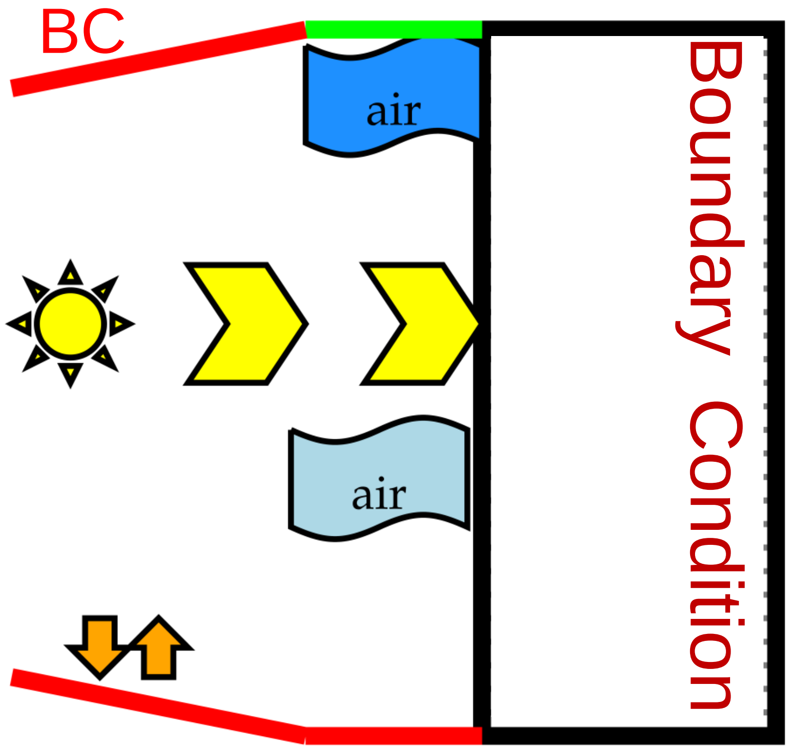


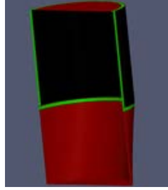
Modelling an open volumetric cavity receiver

- **Key features:**
- Porous absorber structure has a very small length scale
  → absorber behavior as BC
  → **wall** for radiation model
  → **outlet** for fluid simulation

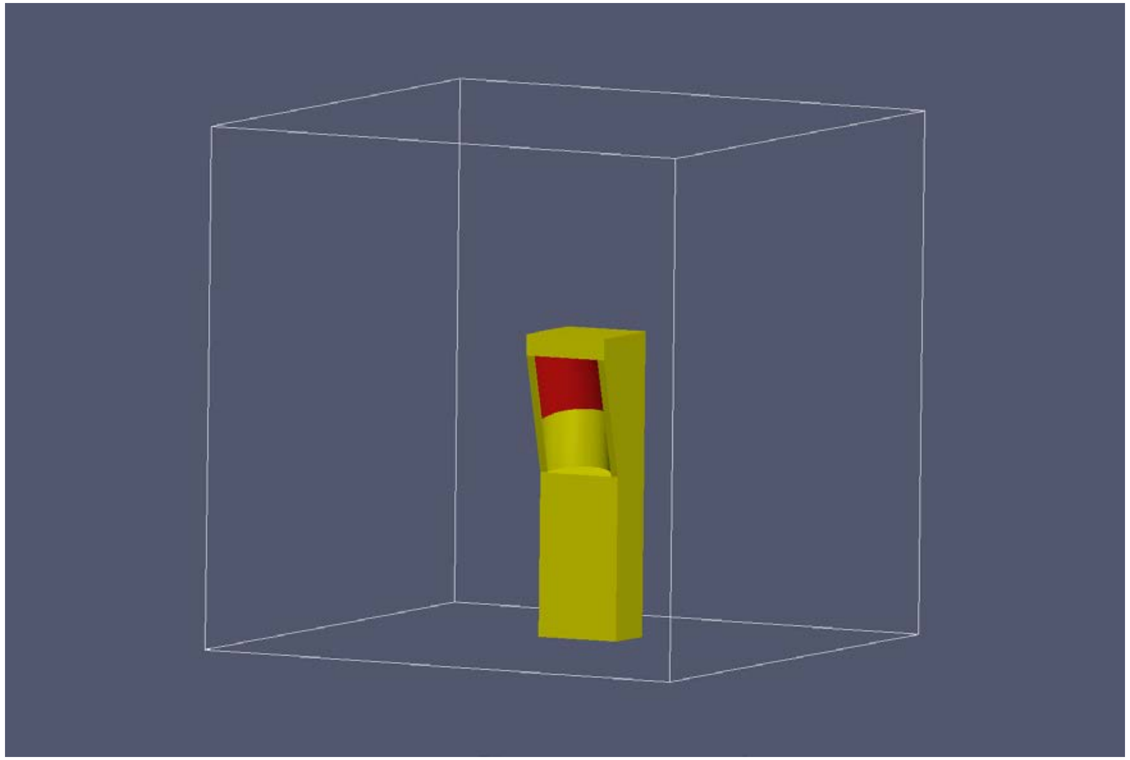
- Heliostat field included as source term for radiation model

- **Wall temperatures** connect the radiation model with the fluid domain→ wall behavior condensed in a BC





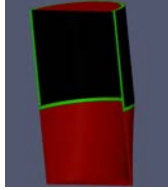
Setup of the simulation



- **Cavity as test configuration**
- **Environment**
  - Air 27°C
- **Solver**
  - OpenFOAM 2.3.0
  - buoyantPimpleFoam
- **Radiation**
  - Viewfactor

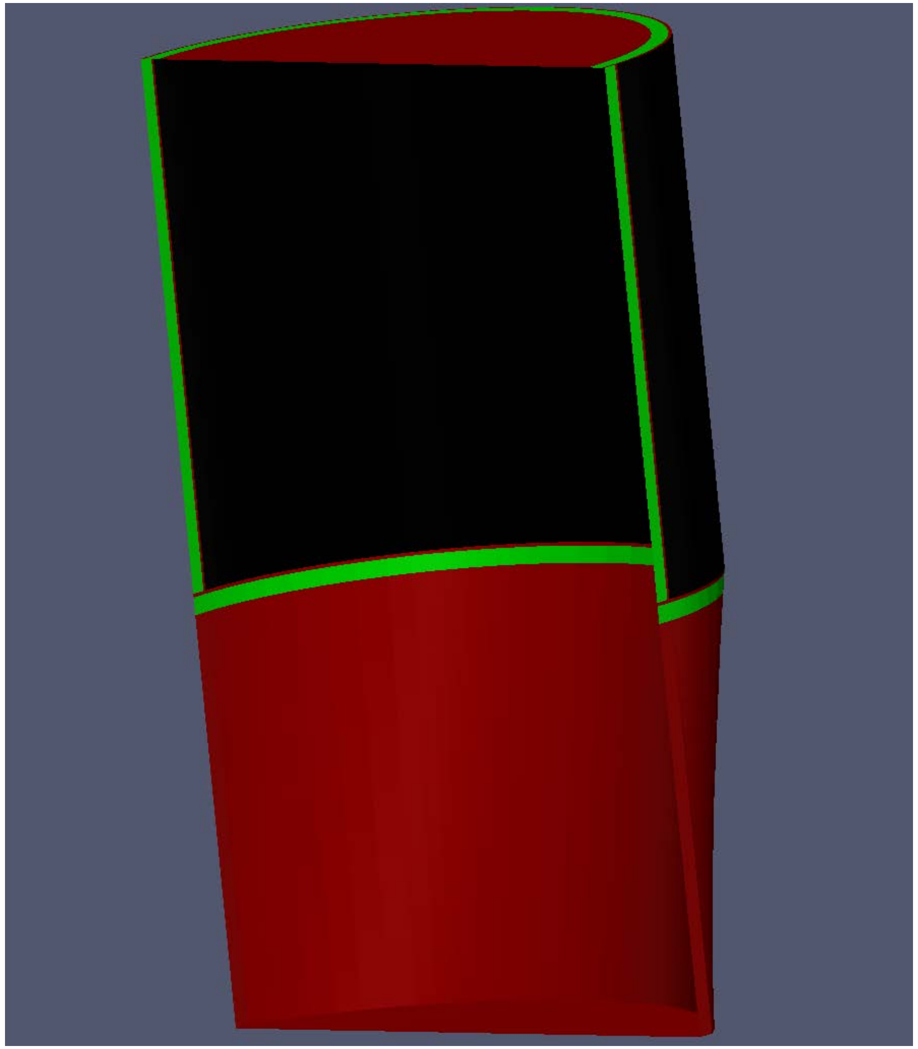
- **Turbulence model**
  - k-ω-SST
  - Prt=0.85

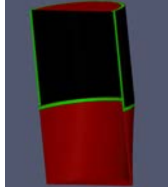
- **Turbulent wall functions:**
  - compressible::kqRWallFunction
  - compessible::omegaWallFunction
  - mutkWallFunction
  - calculated (alphat)



Geometry

- Patches:
  - Porous absorber area
  - Inlets of returning air
  - Thermal active walls (included in viewfactor calculation)



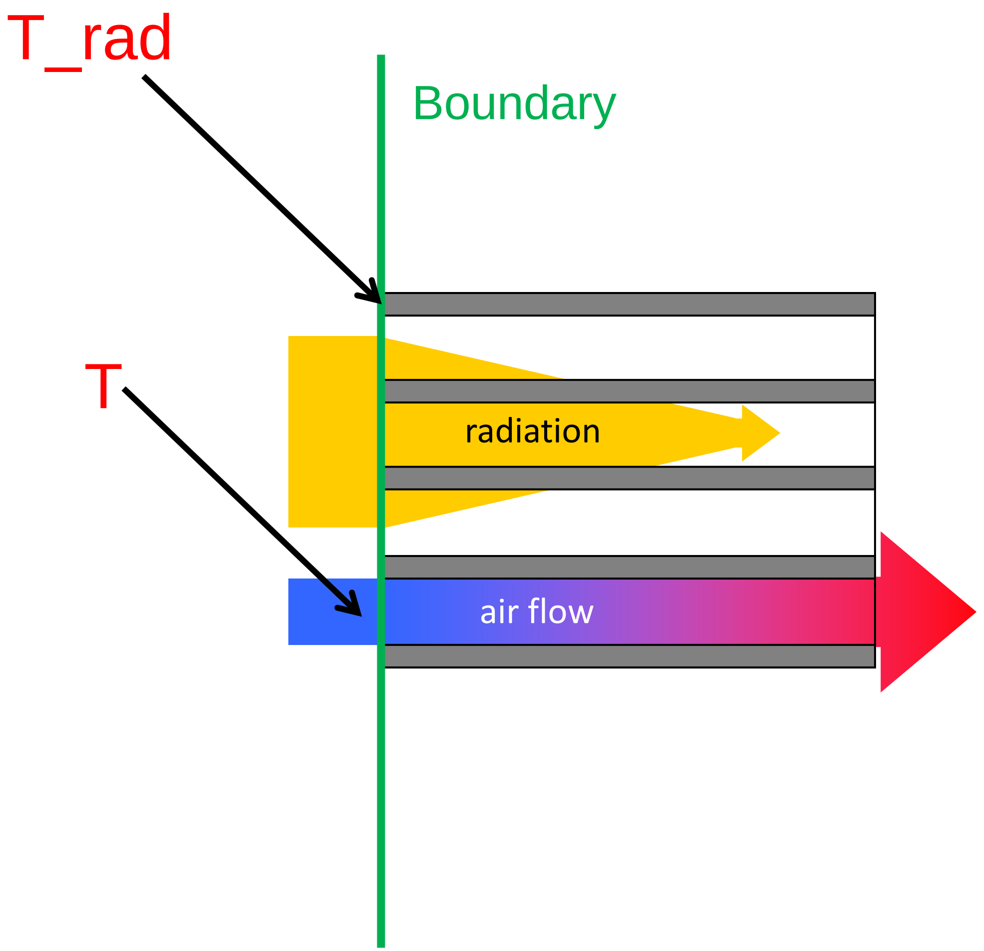


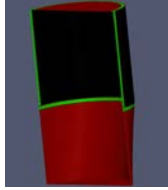
Absorber patch - Outlet

- Introduce a second temperature field into the simulation

- T for fluid model and T_rad for radiation

- T_rad can be calculated by a lookup table which describes the thermal behavior of the ceramic material





Boundary Condition for thermal active walls

- Conservation of energy

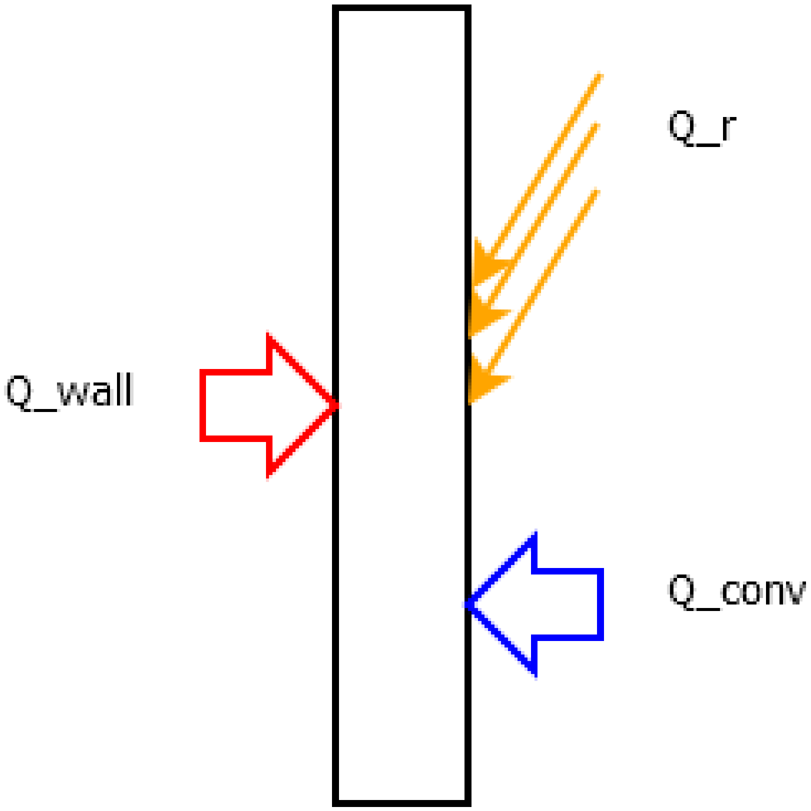
$$Q_r + Q_{wall} + Q_{conv} = 0$$

$$Q_r + k_{\mathrm{wall}}\left(T_{\mathrm{out}} - T_{\mathrm{w}}\right) + \frac{\alpha_{\mathrm{Eff}} c_{\mathrm{pw}}}{y}\left(T_{\mathrm{F}} - T_{\mathrm{w}}\right) = 0$$

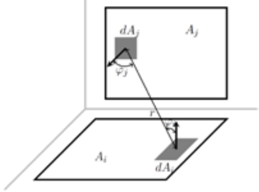
- Substitution of the net-radiation heat flux Qr

$$\begin{aligned} Q_{\mathrm{r}} &= G - J \\ &= G - \epsilon\sigma T_w^4 - (1-\epsilon)G \\ &= \underbrace{\epsilon G}_{:=Q_{\mathrm{abs}}} - \epsilon\sigma T_{\mathrm{w}}^4 \end{aligned}$$

- Solve the boundary condition using the Newton method to determine the root at each update step



K_wall = 0 → Adiabatic wall

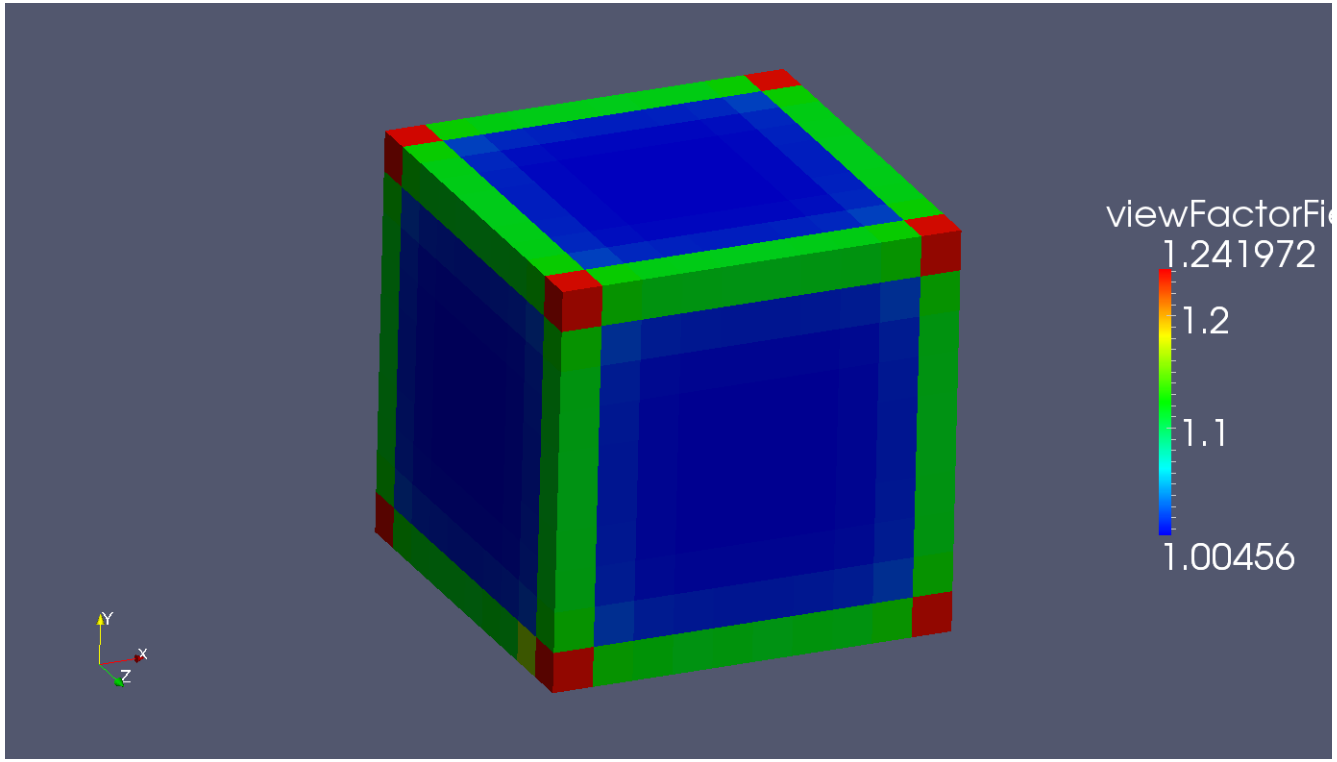


Radiation model - Viewfactor

- to calculate the radiation losses the provided viewfactor model is not accurate enough
→ adapted model

- Radiation is not lost in a closed system

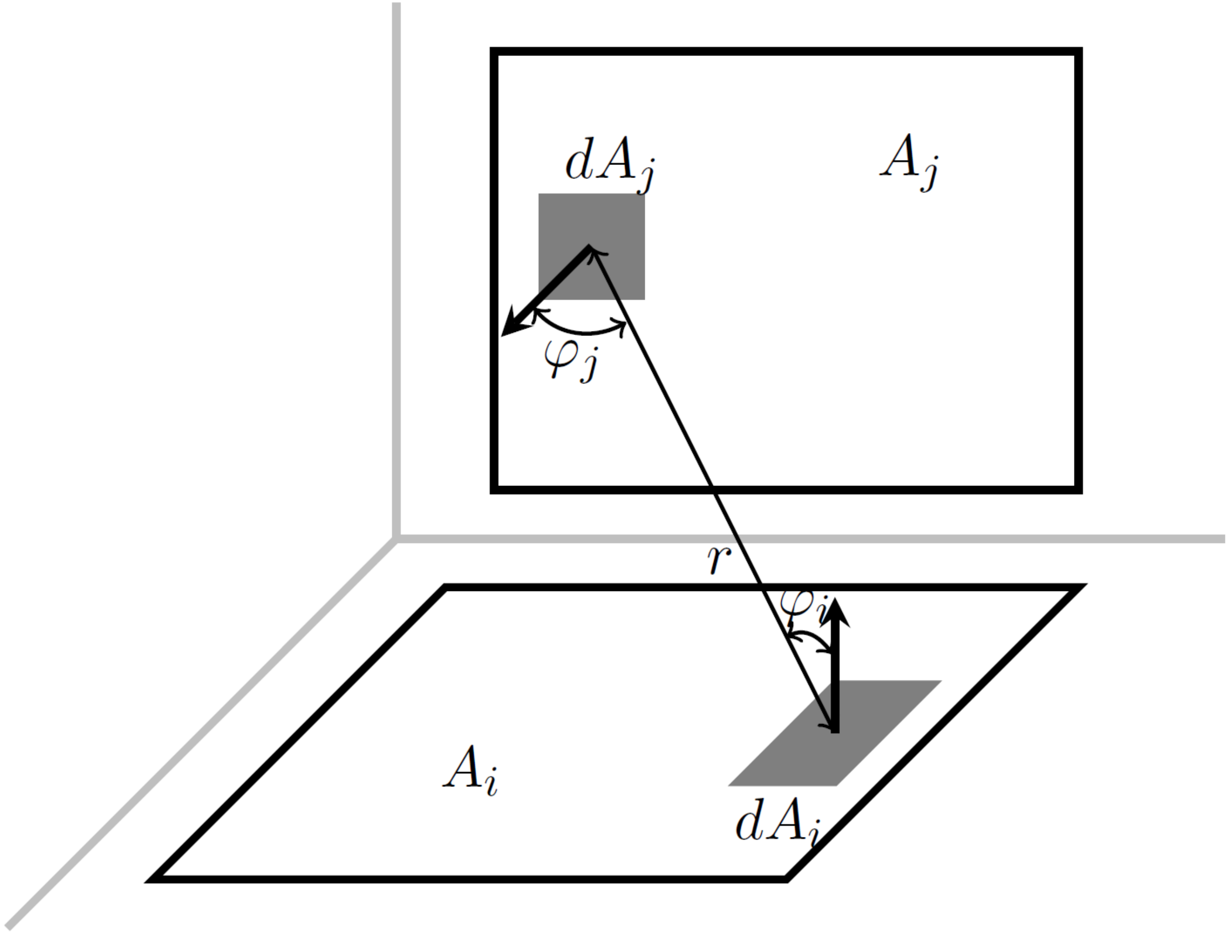
$$\sum_j \Phi_{kj} = 1$$

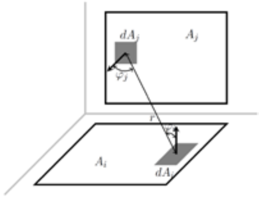


Calculation of viewfactors

- Prerequisite:
  - All surfaces must be modeled as grey diffusive
- Distribution of radiation is **just a function of geometry**

$$\Phi_{ij} = \frac{1}{\pi A_i} \int \int \frac{cos(\varphi_i) cos(\varphi_j)}{r^2} dA_i dA_j$$





Calculating viewfactors

2LI

[1],[3]

$$\Phi_{ij} = \frac{1}{2\pi A_i} \int \int ln(r) d\boldsymbol{s}_i d\boldsymbol{s}_j$$

2AI

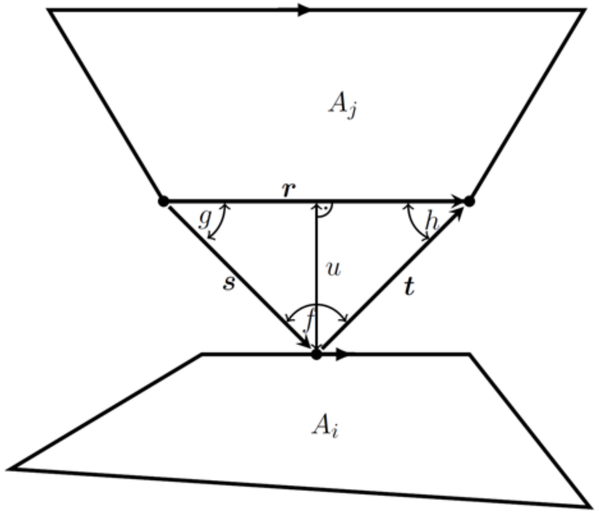
- Using constant mean values for the integrand

$$\Phi_{ij} = \frac{1}{\pi A_i} \int \int \frac{cos(\varphi_i)cos(\varphi_j)}{r^2} dA_i dA_j$$
$$\approx \frac{1}{\pi A_i} \int \int \frac{cos(\tilde{\varphi}_i)cos(\tilde{\varphi}_j)}{\tilde{r}^2} dA_i dA_j$$

Stokes Theorem

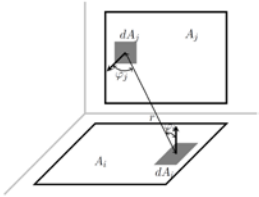
Solving one integral

1LI

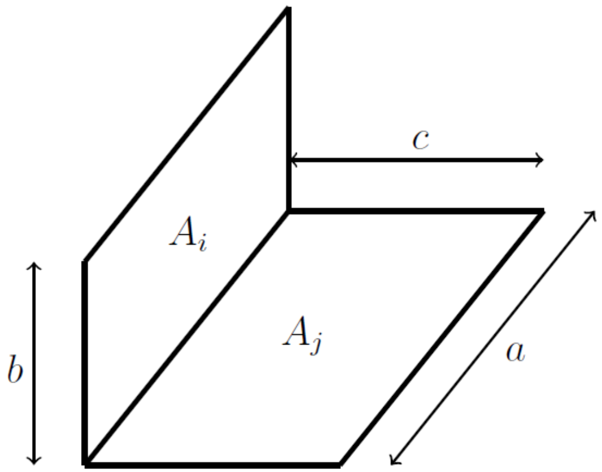


$$\Phi_{ij} = \frac{1}{2\pi A_i} \sum_{n=1}^{M_i} \sum_{m=1}^{M_j} cos(\Psi_{nm}) \int ln\Big(\|\boldsymbol{t}\| \, cos \quad |) + uf - \|\boldsymbol{r}\| \Big) d\boldsymbol{s}_i$$

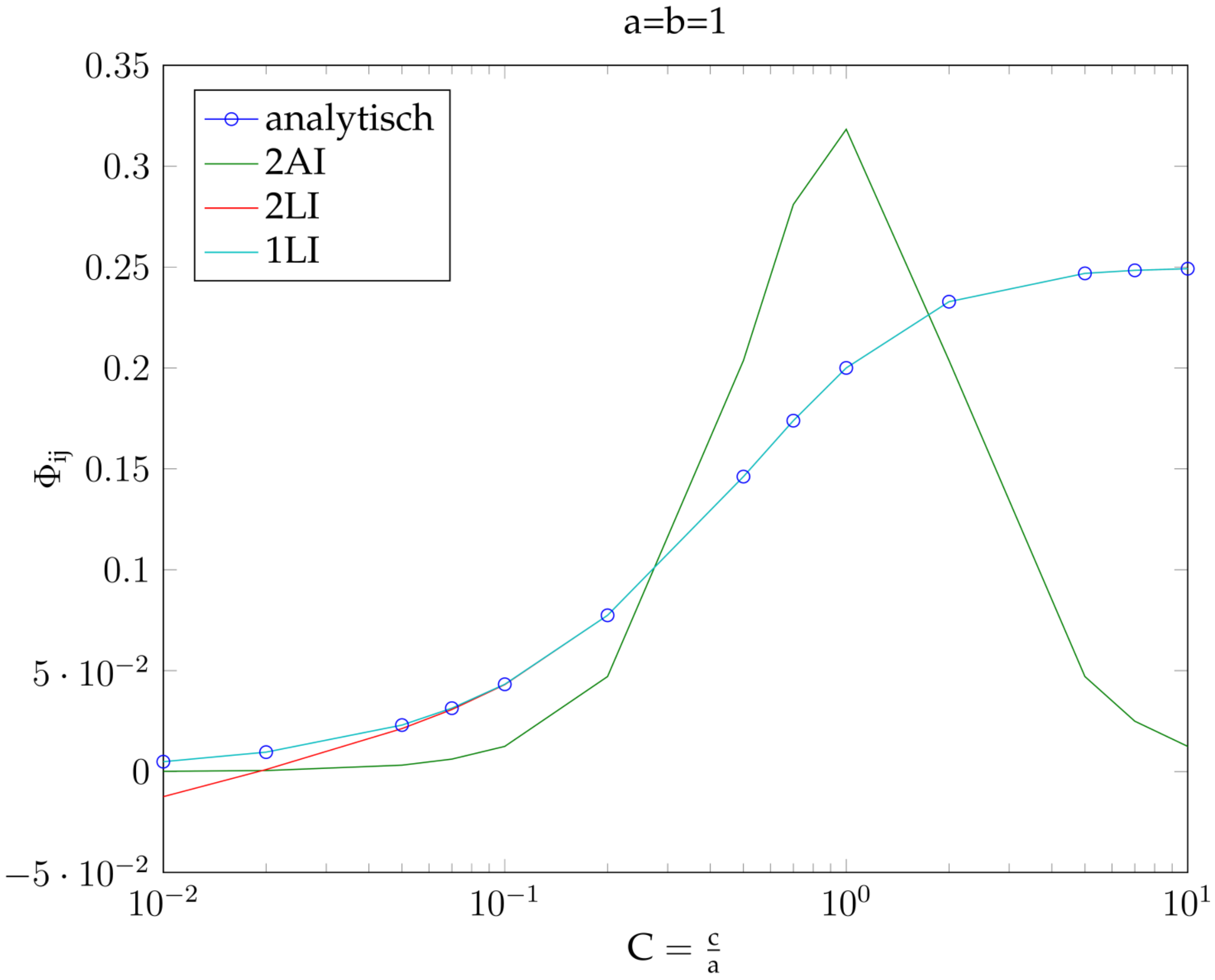
[2]

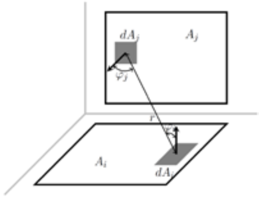


Reference configuration

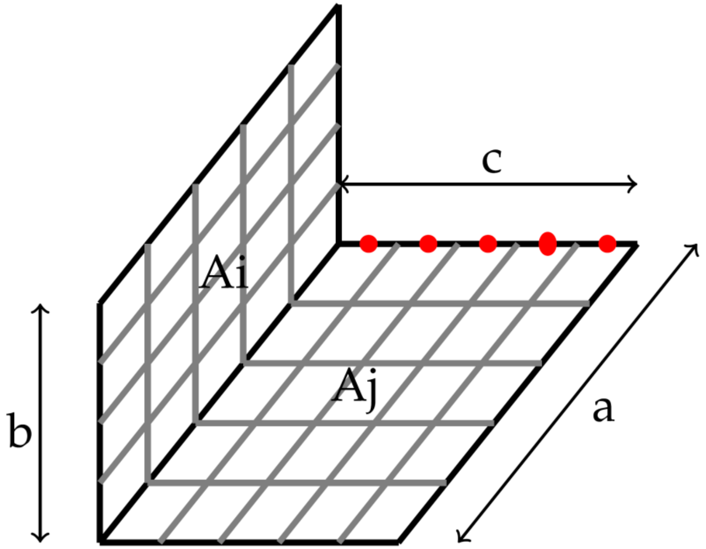


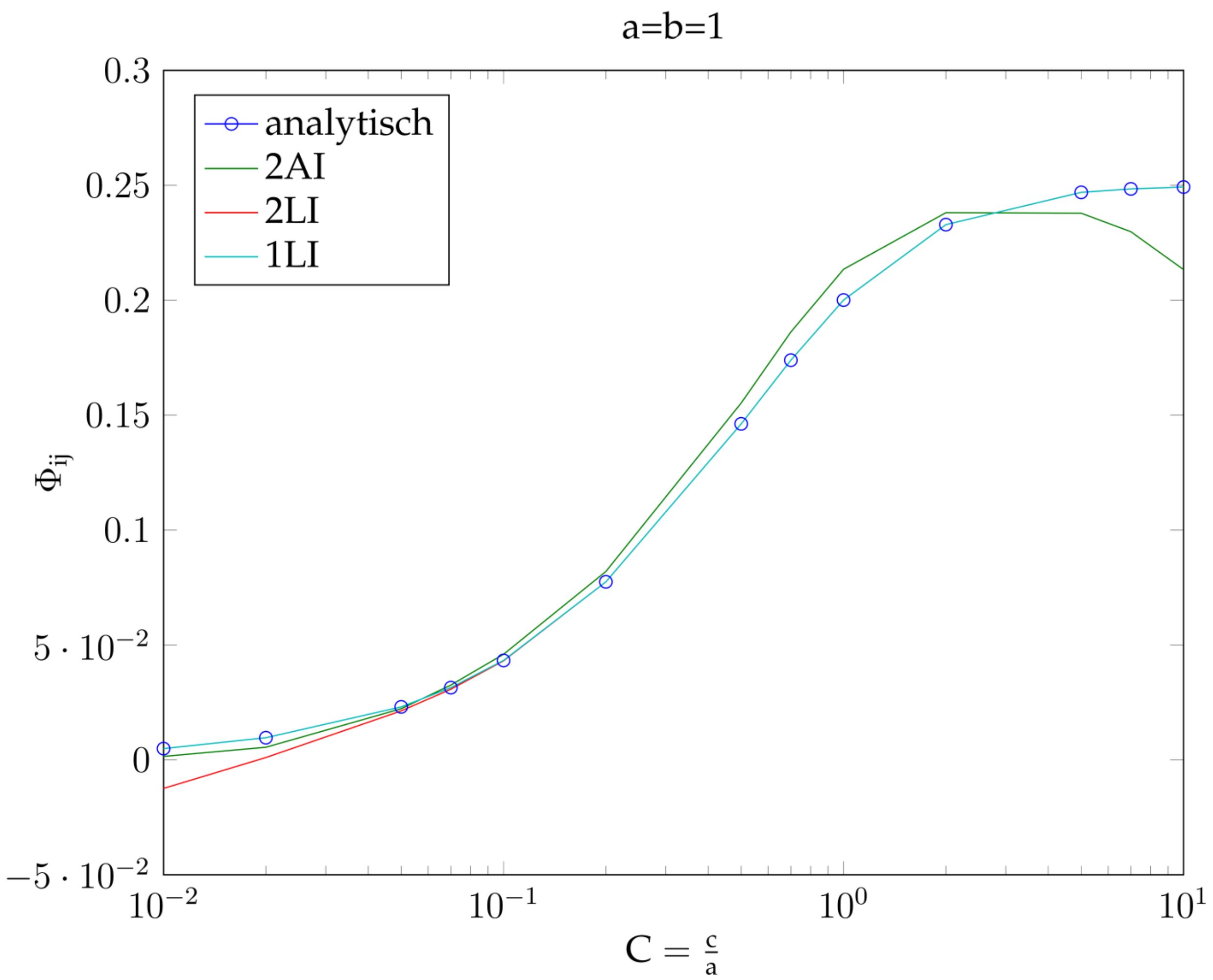
[4]

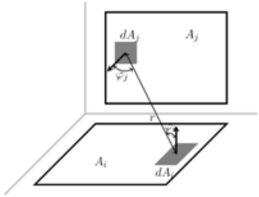




Reference configuration

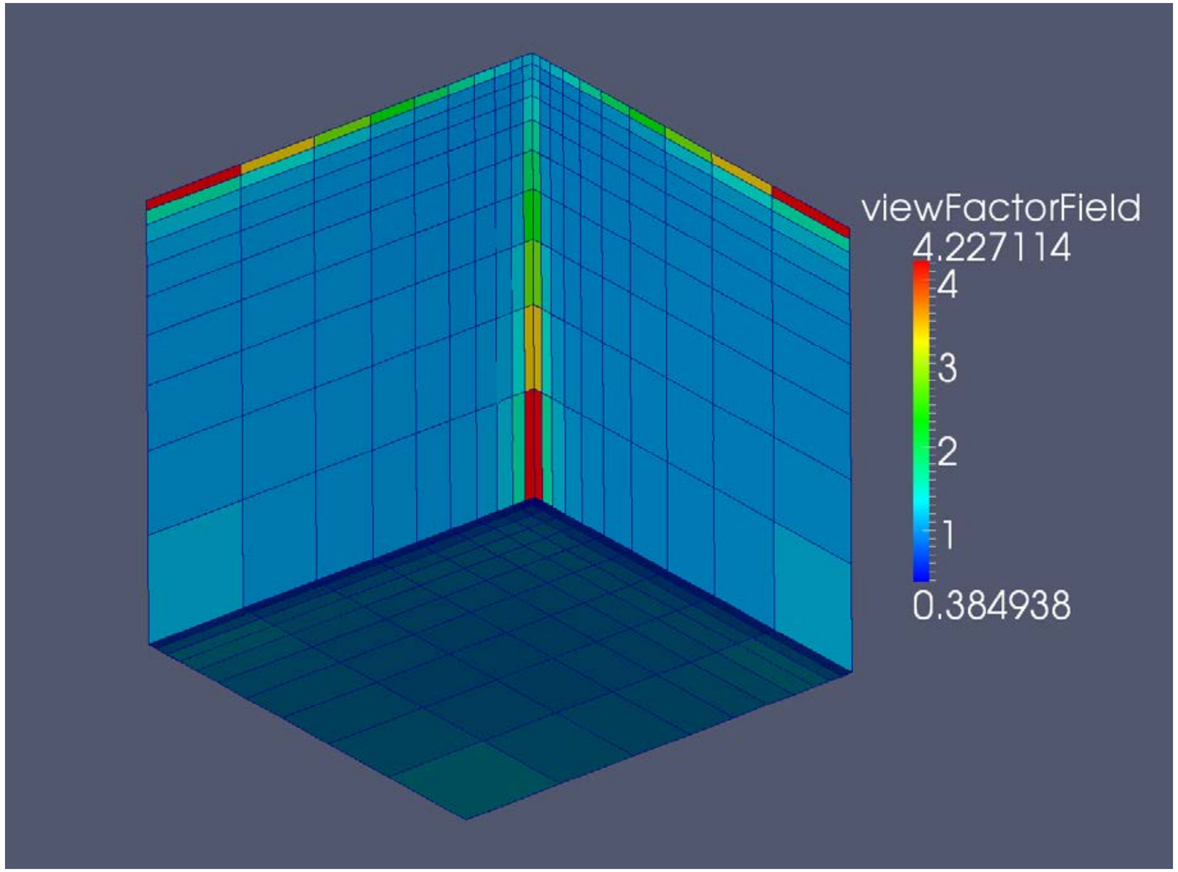




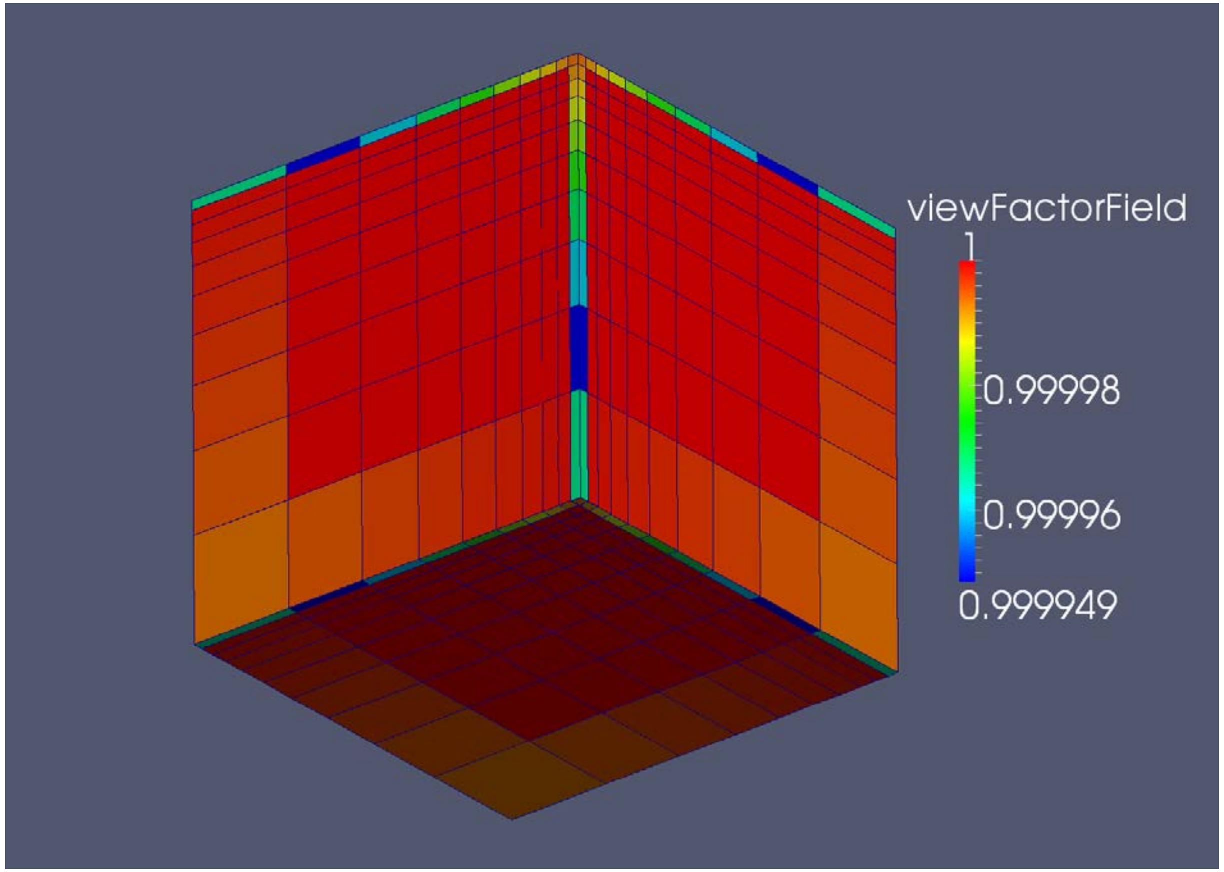


Comparing the sum of viewfactors

- 2AI

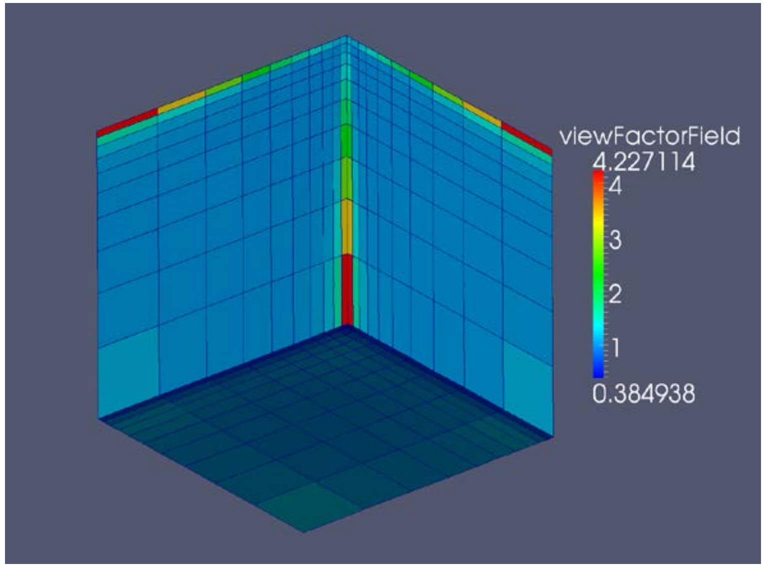


- 1LI

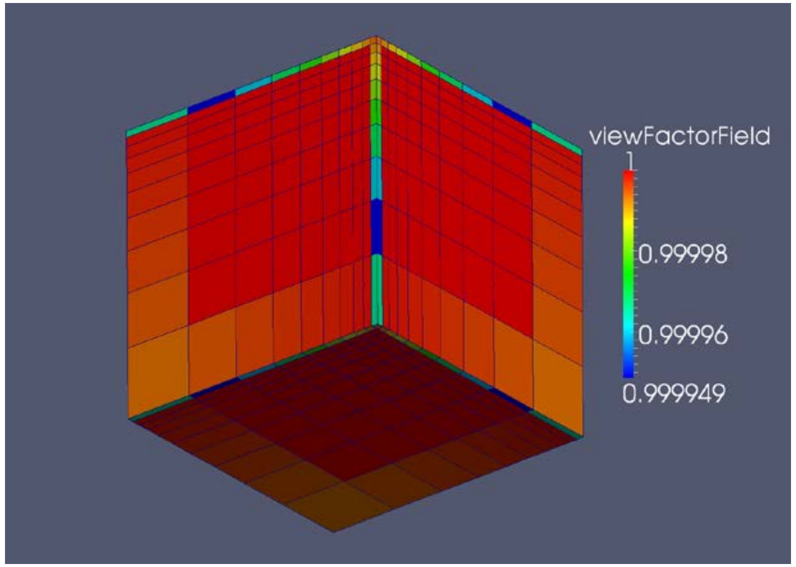


Comparing the sum of viewfactors

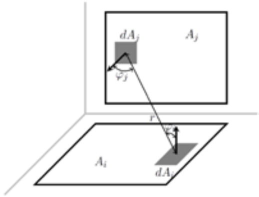
- 2AI



- 1LI

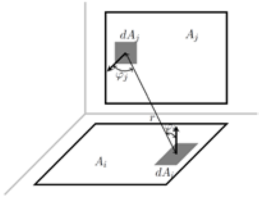


0,5896min	6x6x6 cube (38880 combinations)	0,884min
1,876min	7x7x7 cube (84035 combinations)	1,232min



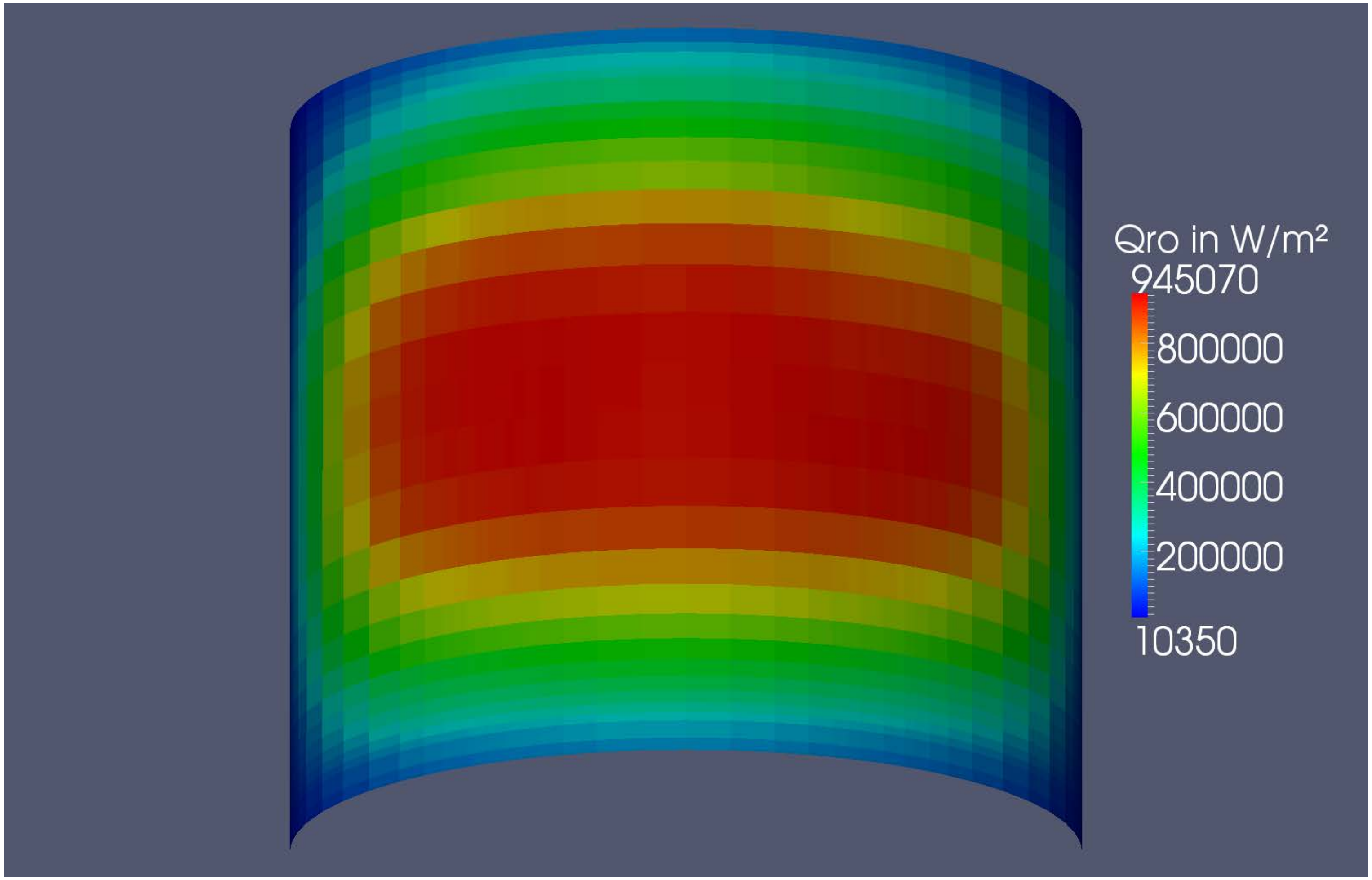
Calculation of viewfactors

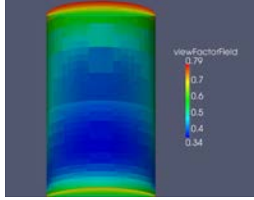
2AI	2LI	1LI
No numerical integration	Gaussian integration for 2 faces	Gaussian integration for 1 face
	Accuracy	
	Computational Efficiency	
	Special treatment in the case that two faces have a common edge	Special treatment in the case that two faces have a common edge



Absorber patch - Outlet

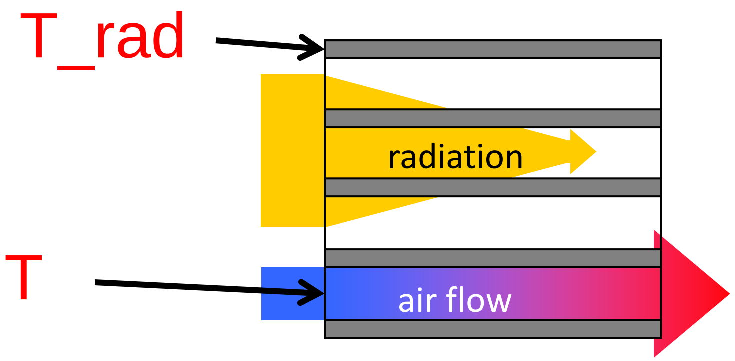
- External radiation from the heliostat field is calculated using an external ray tracer
- Use value **Qro** of the **greyDiffusiveBoundaryCondition** to include the external radiation



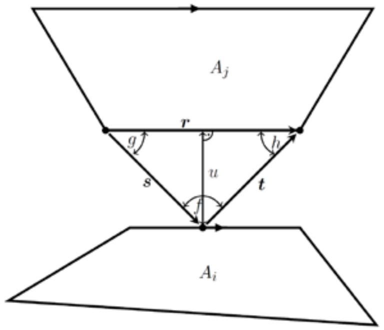


At a glance

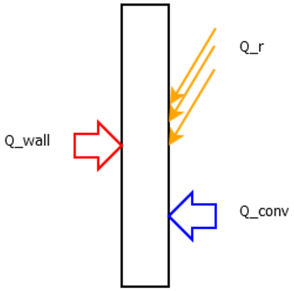
- Extra temperature T_rad



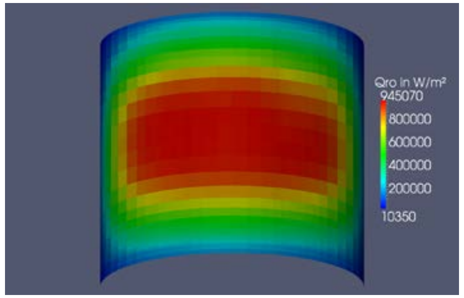
- Adapted viewfactor model

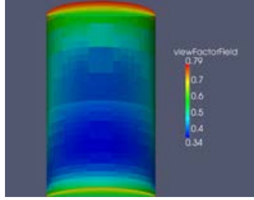


- BC for thermal active walls and absorber patch



- Radiation Source term



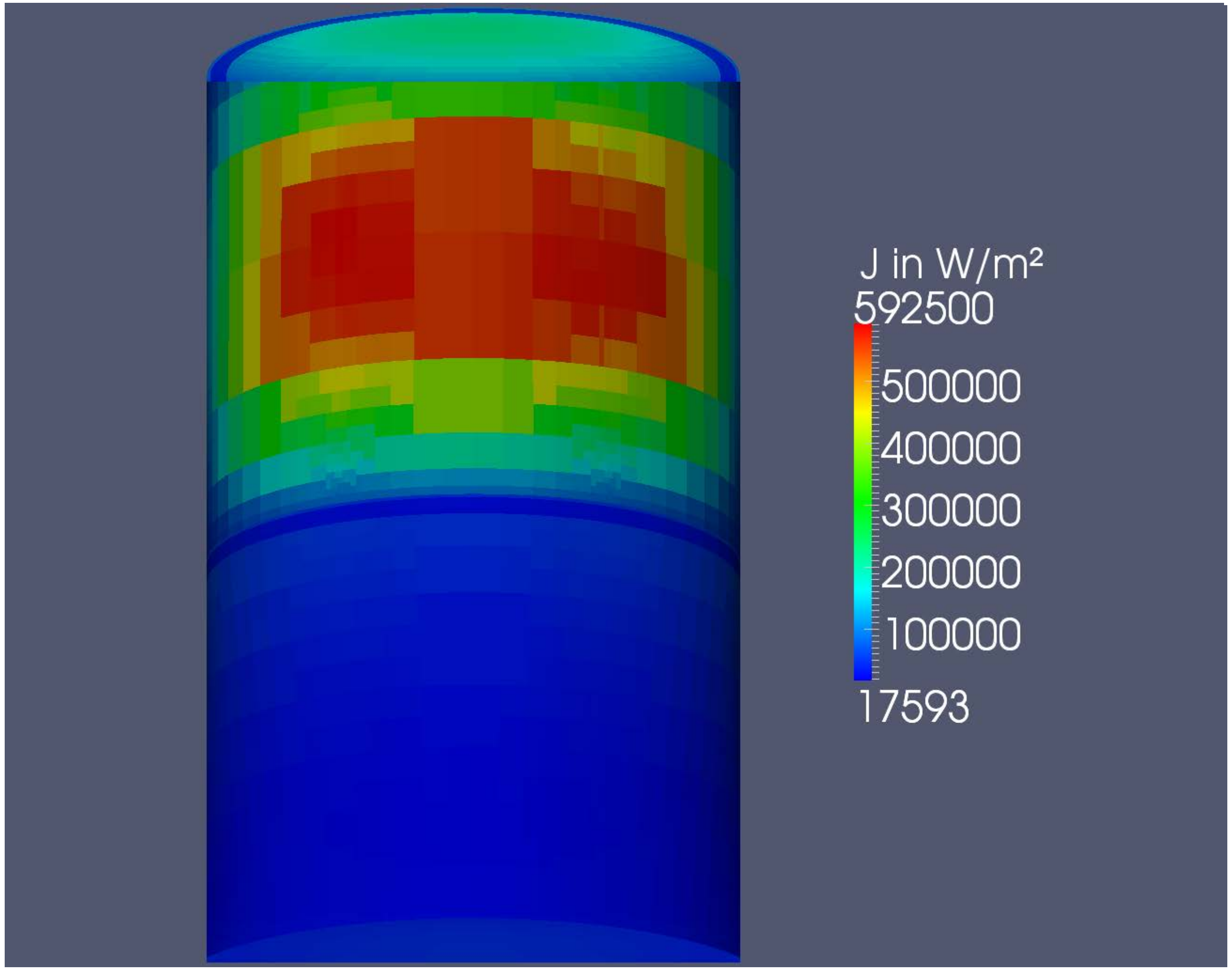


Results

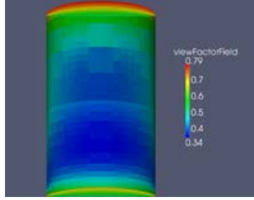
- Calculation of viewfactors
    - Distribution and values are reasonable

- Only the cavity was included in the viewfactor calculation, losses to the environment can therefore be calculated by

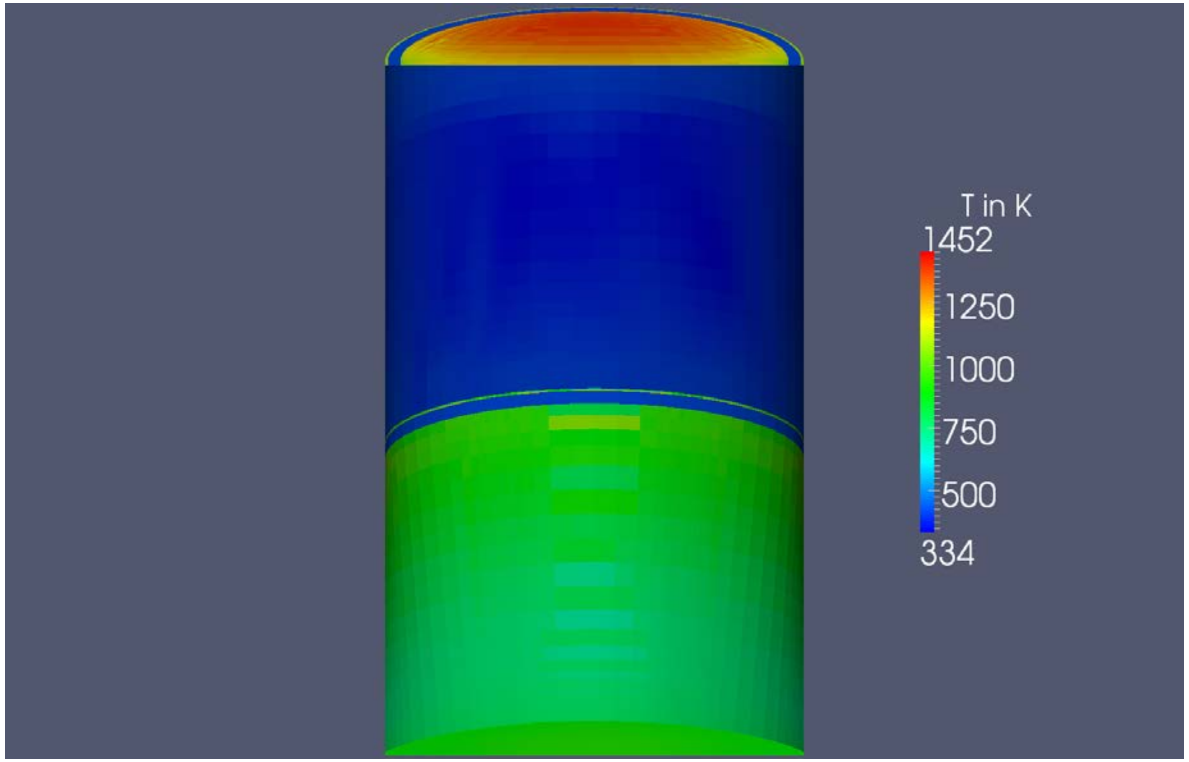
$$J_{loss} = \sum_k J_k \left(1 - \sum_j \Phi_{kj}\right)$$



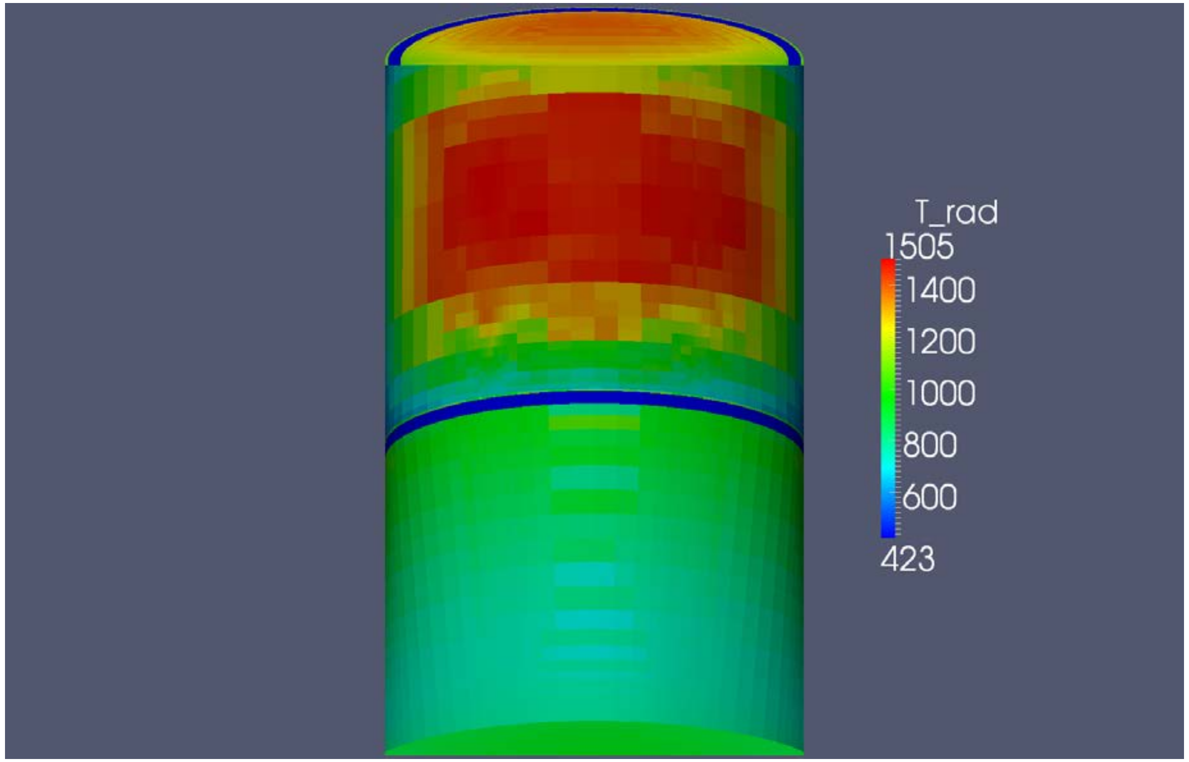
DLR



Results



T



T_rad

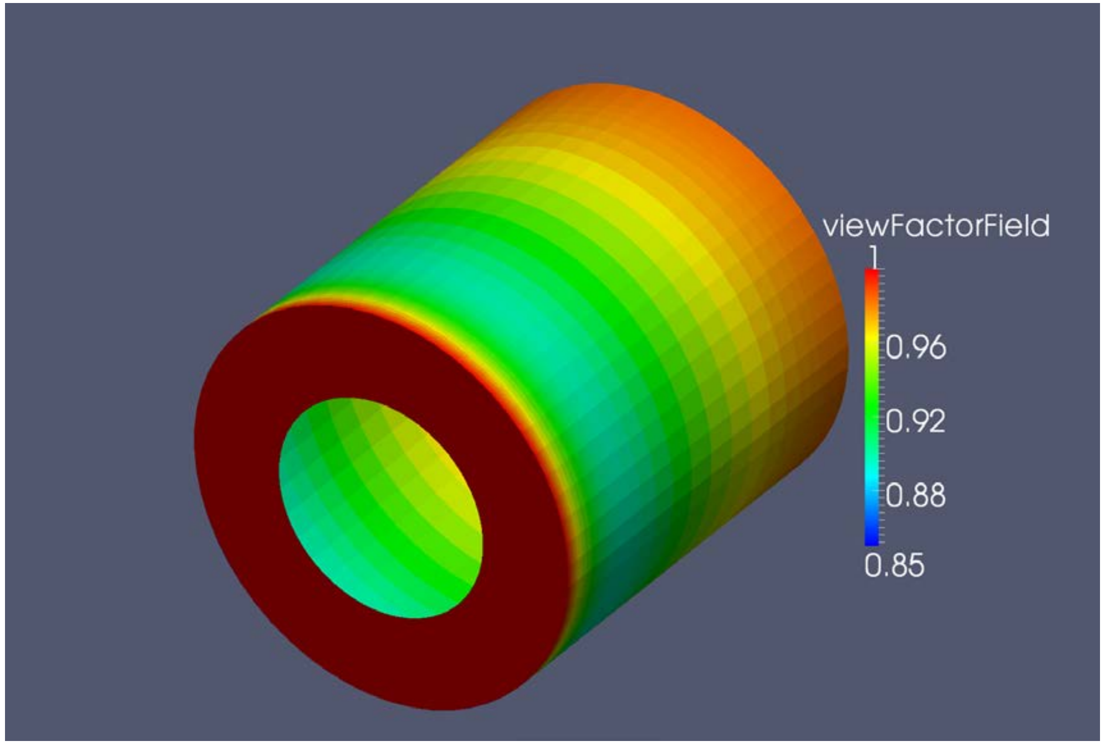
Summary

- **OpenFOAM**
  - is highly adaptable
  - allows complex boundary conditions
  - accurate viewfactor calculation possible

- **Solar Receivers**
- Convective and radiative losses can be calculated using OpenFOAM

- It is possible to compare different receiver configurations

- **OpenFOAM can be a valuable development tool in solar research**



Thank you for your attention.
Questions?

Ministerium für Innovation,
Wissenschaft und Forschung
des Landes Nordrhein-Westfalen

Project Start-SF
contract 323-2010-006

Backup

Literature

[1] S. Mazumder and M. Ravishankar. General procedure for calculation of diffuse view factors between arbitrary planar polygons. *Int. J. Heat Mass Transfer*, 2012. URL http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.07.066.

[2] G.P. Mitalas and D.G. Stephenson. Fortran iv programs to calculate radiant energy interchange factors. Technical report, National Research Council Canada Division of Building Research, 1966.

[3] Ephraim M Sparrow. *Radiation Heat Transfer*. Hemisphere Publishing Corporation, 1978.

[4] Verein Deutscher Ingenieure VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (GVC), editor. *VDI Heat Atlas*. Springer, second edition, 2010.

[5] George N. Walton. Calculation of obstructed view factors by adaptive integration. *National Institute of Standards and Technology, NISTIR 6925*, 2002.