Heat Transfer: Radiation

Example: Radiation Protective Shield

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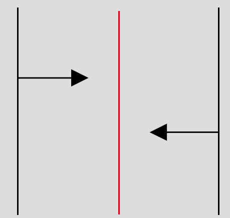
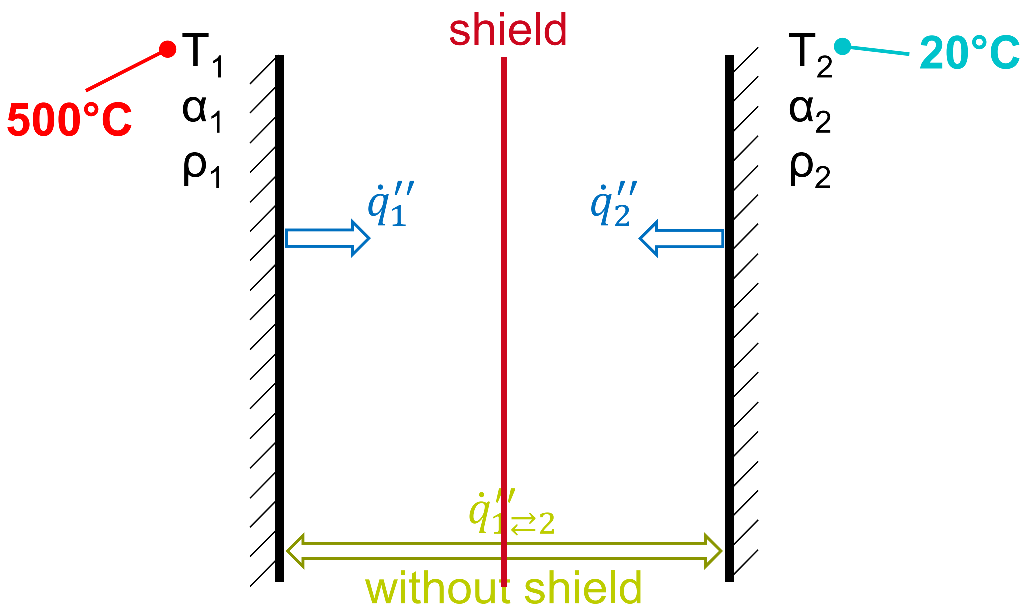
Learning goals

Radiation Protective Shield:

- How well can radiation be shielded and which properties make a good radiation protective shield (in the case of two parallel plates)?



Initial situation

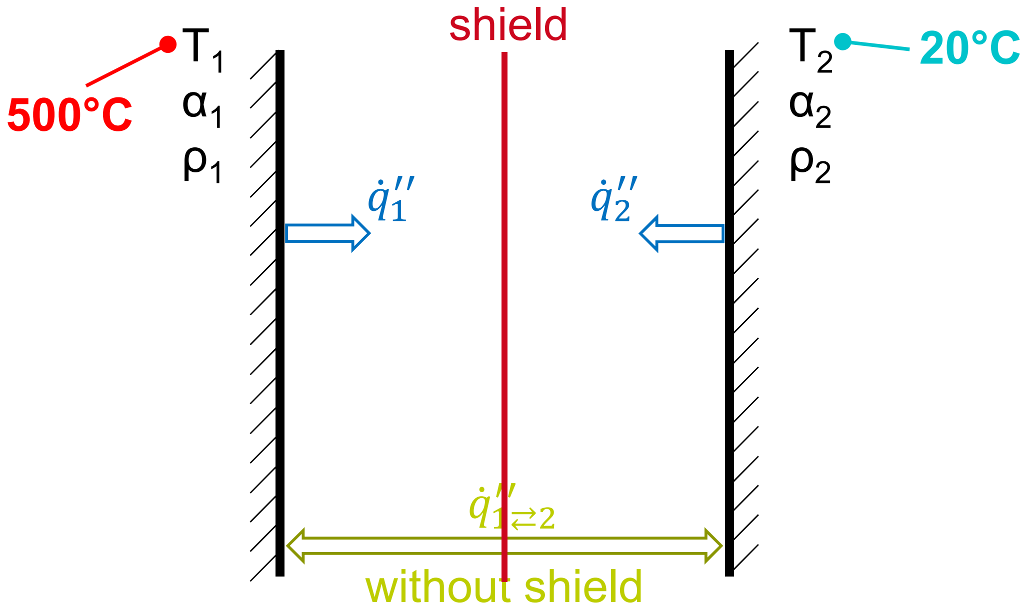


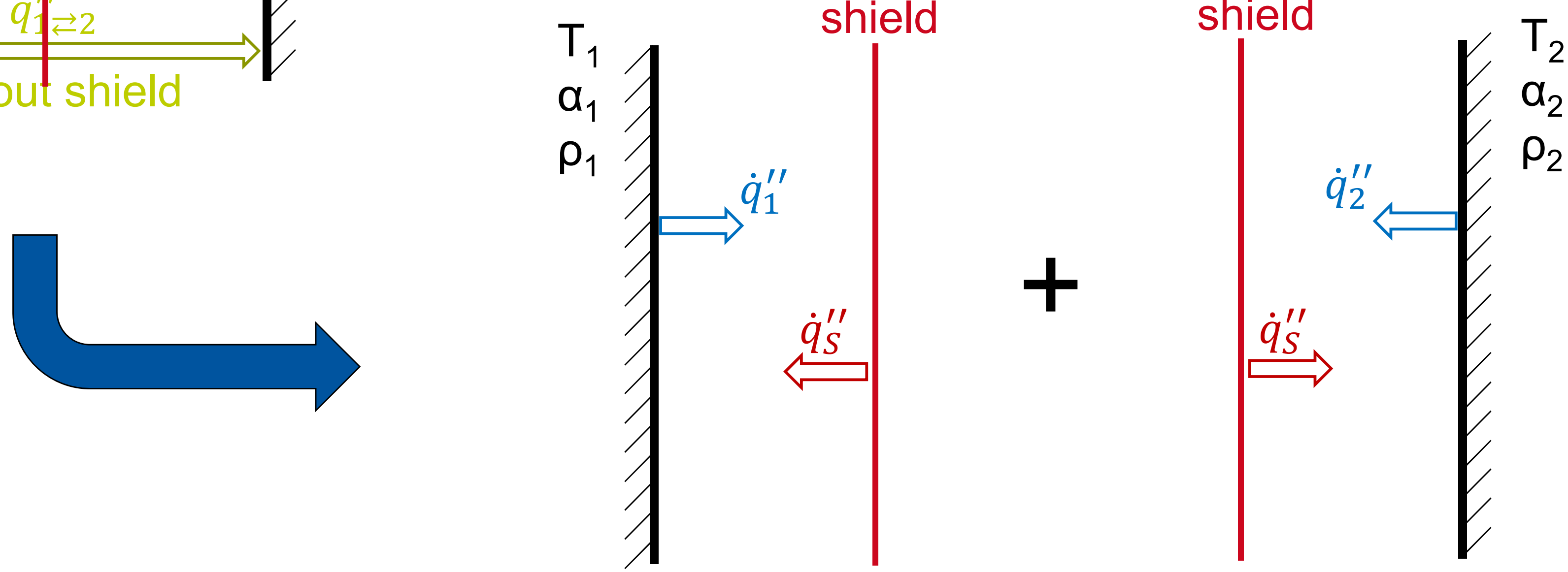
how can the cold plate stay permanently at 20°C?

or with strong cooling
(we will see in the next chapters) or

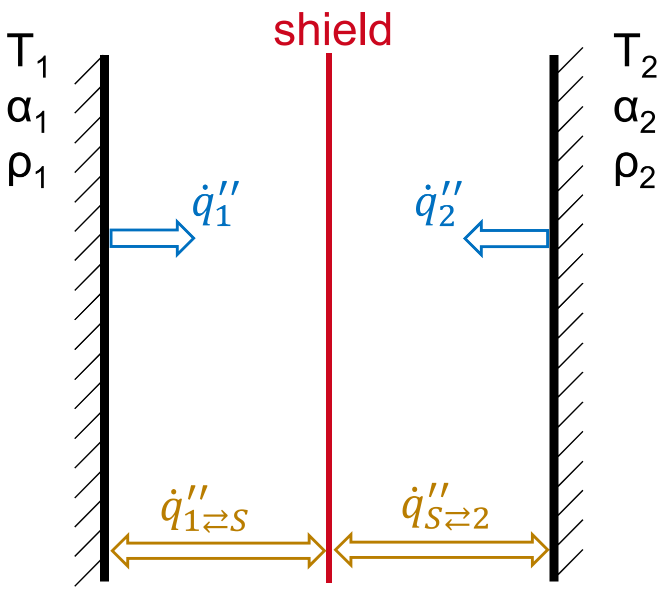
→ with protective shield

Initial situation





Protective shield: Derivation

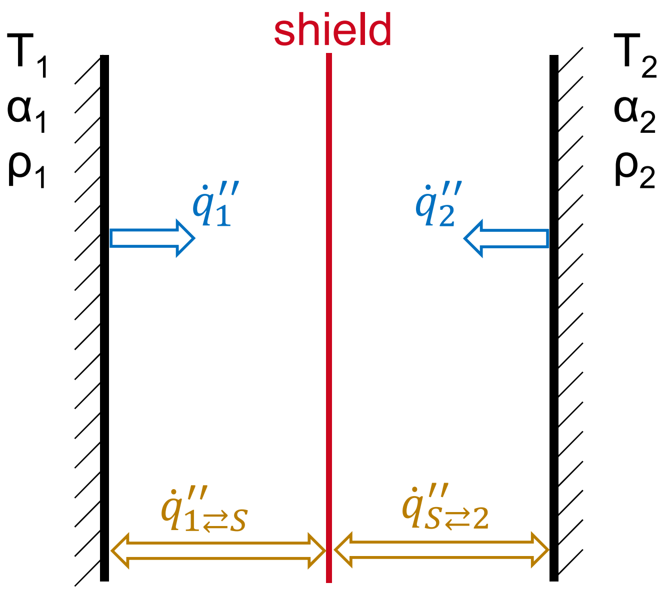


Net heat flow shield - plates:

$$\dot{q}_{1\rightleftarrows s}'' = \frac{\sigma\,(T_1^4 - T_s^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_s} - 1}$$

$$\dot{q}_{s\rightleftarrows 2}'' = \frac{\sigma\,(T_s^4 - T_2^4)}{\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_2} - 1}$$

Protective shield: Derivation



Net heat flow shield - plates:

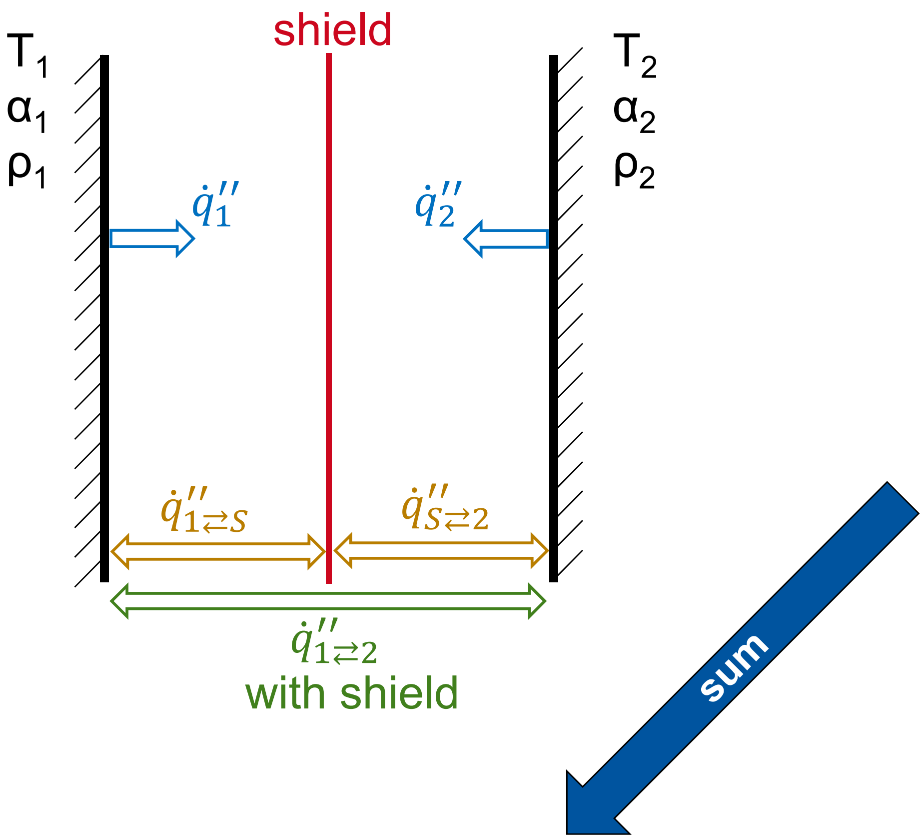
$$\dot{q}_{1\rightleftarrows s}'' = \frac{\sigma\left(T_1^4 - T_s^4\right)}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_s} - 1}$$

$$\dot{q}_{s\rightleftarrows 2}'' = \frac{\sigma\left(T_s^4 - T_2^4\right)}{\dfrac{1}{\varepsilon_s} + \dfrac{1}{\varepsilon_2} - 1}$$

Coupling at shield:

$$\dot{q}_{1\rightleftarrows 2}'' = \dot{q}_{1\rightleftarrows s}'' = \dot{q}_{s\rightleftarrows 2}''$$

Protective shield: Derivation



Net heat flow shield - plates:

$$\dot{q}''_{1\rightleftarrows s}\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_s}-1\right)=\sigma\,(T_1^4-T_s^4)$$

$$\dot{q}''_{s\rightleftarrows 2}\left(\frac{1}{\varepsilon_s}+\frac{1}{\varepsilon_2}-1\right)=\sigma\,(T_s^4-T_2^4)$$

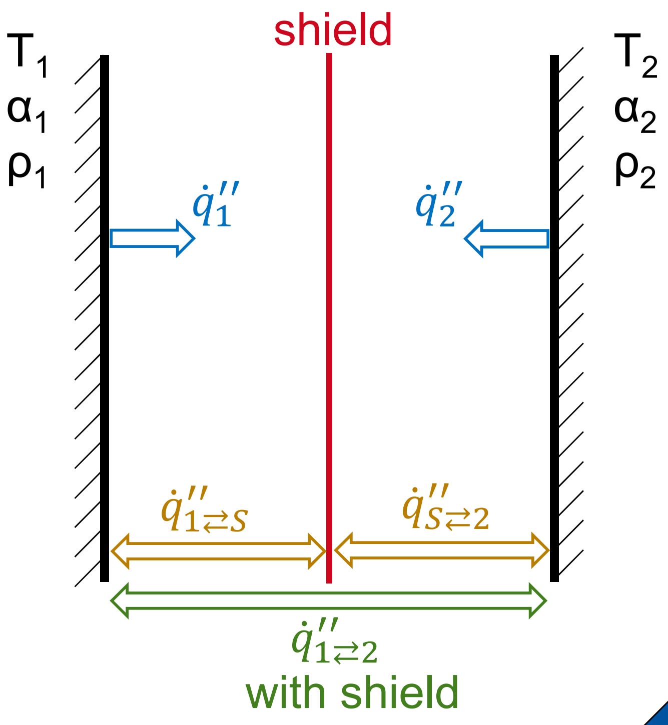
Coupling at shield:

$$\dot{q}''_{1\rightleftarrows 2}=\dot{q}''_{1\rightleftarrows s}=\dot{q}''_{s\rightleftarrows 2}$$

Elimination of T_S :

$$\dot{q}''_{1\rightleftarrows s}\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_s}-1\right)+\dot{q}''_{s\rightleftarrows 2}\left(\frac{1}{\varepsilon_s}+\frac{1}{\varepsilon_2}-1\right)=\sigma\,(T_1^4-T_2^4)$$

Protective shield: Derivation outcome



Net heat flow shield - plates:

$$\dot{q}''_{1\rightleftarrows s}\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_s}-1\right)=\sigma\left(T_1^4-T_s^4\right)$$

$$\dot{q}''_{s\rightleftarrows 2}\left(\frac{1}{\varepsilon_s}+\frac{1}{\varepsilon_2}-1\right)=\sigma\left(T_s^4-T_2^4\right)$$

Sum

Coupling at shield:

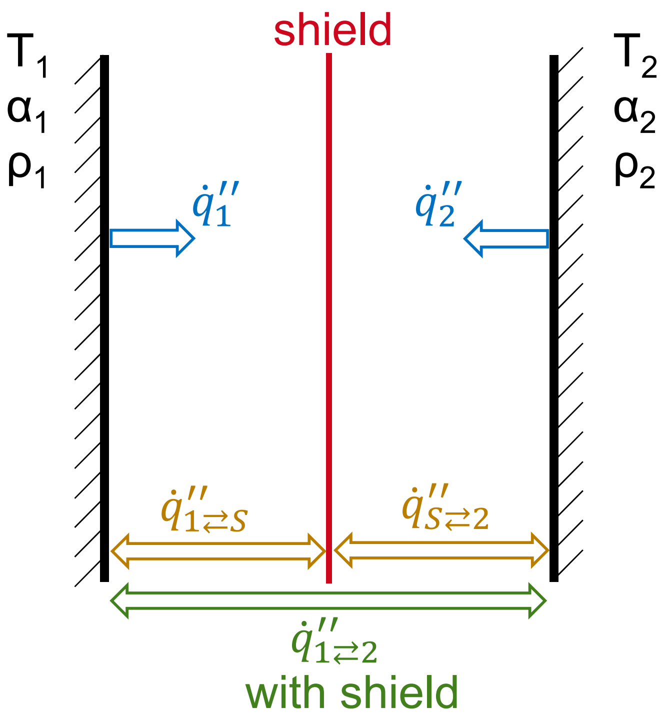
$$\dot{q}''_{1\rightleftarrows 2}=\dot{q}''_{1\rightleftarrows s}=\dot{q}''_{s\rightleftarrows 2}$$

Elimination of T_S :

$$\dot{q}''_{1\rightleftarrows s}\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_s}-1\right)+\dot{q}''_{s\rightleftarrows 2}\left(\frac{1}{\varepsilon_s}+\frac{1}{\varepsilon_2}-1\right)=\sigma\left(T_1^4-T_2^4\right)$$

$$\boxed{\dot{q}''_{1\rightleftarrows 2}=\frac{\sigma\left(T_1^4-T_2^4\right)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}+\frac{2}{\varepsilon_s}-2}}$$

Protective shield: Influence on heat flow



Net heat flow with shield:

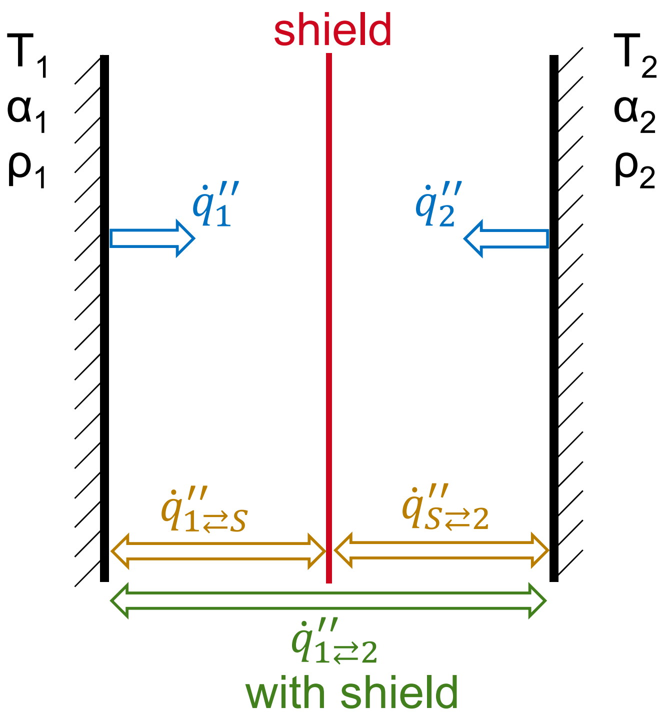
$$\dot{q}''_{1\rightleftarrows s}\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_s}-1\right)=\sigma\left(T_1^4-T_s^4\right)$$

Net heat flow with shield:

$$\dot{q}''_{1\rightleftarrows 2}=\frac{1}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1+\frac{2}{\varepsilon_s}-1}\,\sigma\left(T_1^4-T_2^4\right)$$

effect of shield

Protective shield: necessary properties



Net heat flow with shield:

$$\dot{q}''_{1\rightleftarrows 2} = \underbrace{\boxed{\frac{1}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1+\frac{2}{\varepsilon_S}-1}}}_{\text{determinant pre-factor } f}\sigma\,(T_1^4 - T_2^4)$$

For $\varepsilon_1 = \varepsilon_2 = 0.6$:

a)	*Without shield*	$f = 0.43$
b)	$\varepsilon_S = 1$	$f = 0.3$
c ~~b~~)	$\varepsilon_S = 10^{-5}$	$f = 5 \times 10^{-6}$
d)	$\varepsilon_S = \varepsilon_1 = \varepsilon_2 = 0.6$	$f = ???$

Conclusion:

- Also a black body shield reduces the radiation exchange
- For a high shielding effect the ε should be minimal ➡ high reflectivity

Comprehension Questions

Why is the radiation exchange reduced, even in case of the shield being a black body?

What happens if the three plates have identical radiation properties $(\varepsilon_1 = \varepsilon_2 = \varepsilon_s)$?