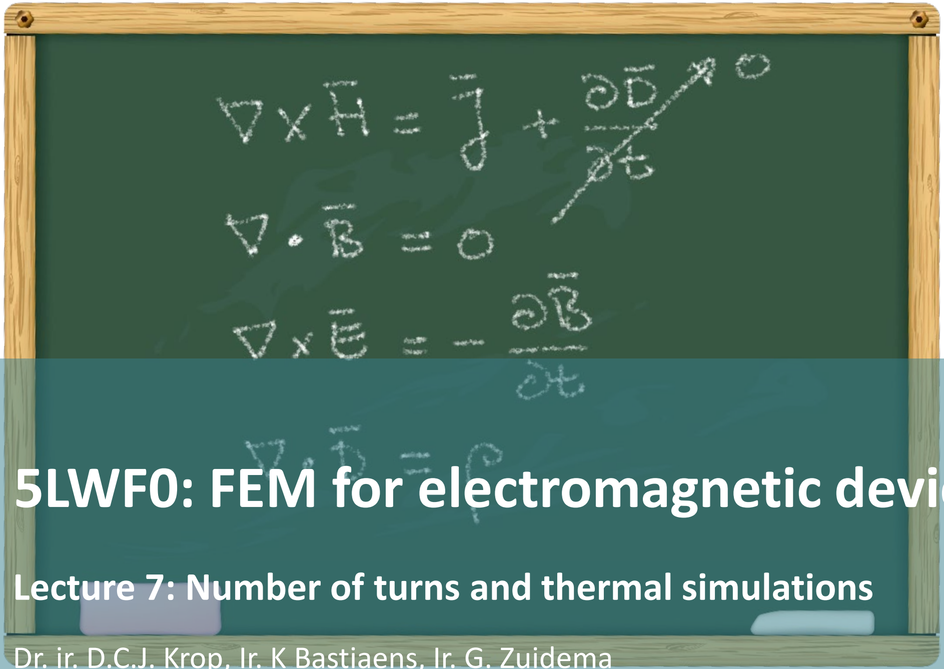

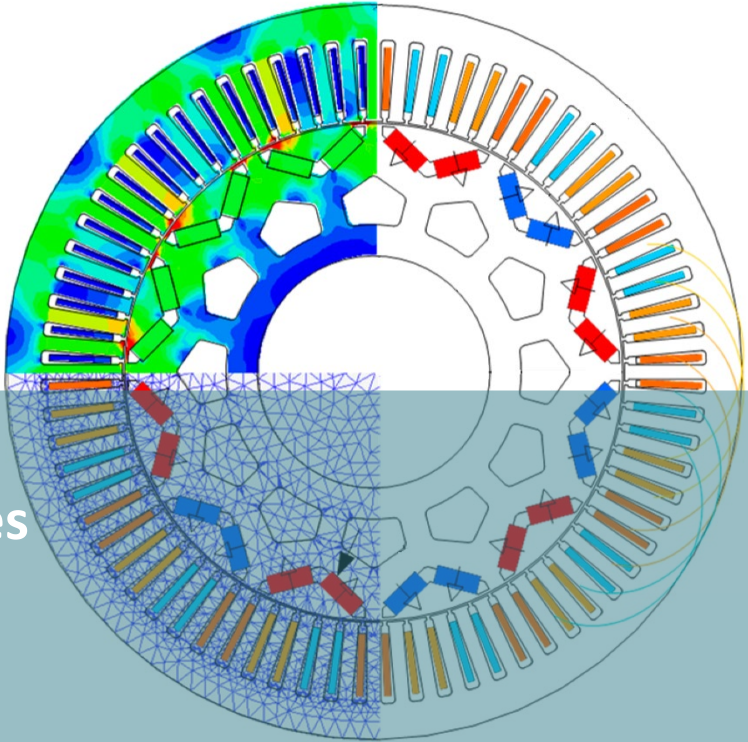

5LWF0: FEM for electromagnetic devices

Lecture 7: Number of turns and thermal simulations

Dr. ir. D.C.J. Krop, Ir. K Bastiaens, Ir. G. Zuidema

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Outline and topics of the previous lecture

Loss mechanism in electrical machines

- Copper losses
- Eddy current losses in conductive **bulk** materials
- Iron/Core losses in **laminated** steel
  - Classical losses (eddy currents in sheets)
  - Hysteresis losses
  - Excess losses

Demagnetization

- Risks of irreversible alternation of permanent magnet material properties under (certain) conditions of operation
- Performing a demagnetization check in FEM

Outline for the lecture of week 7

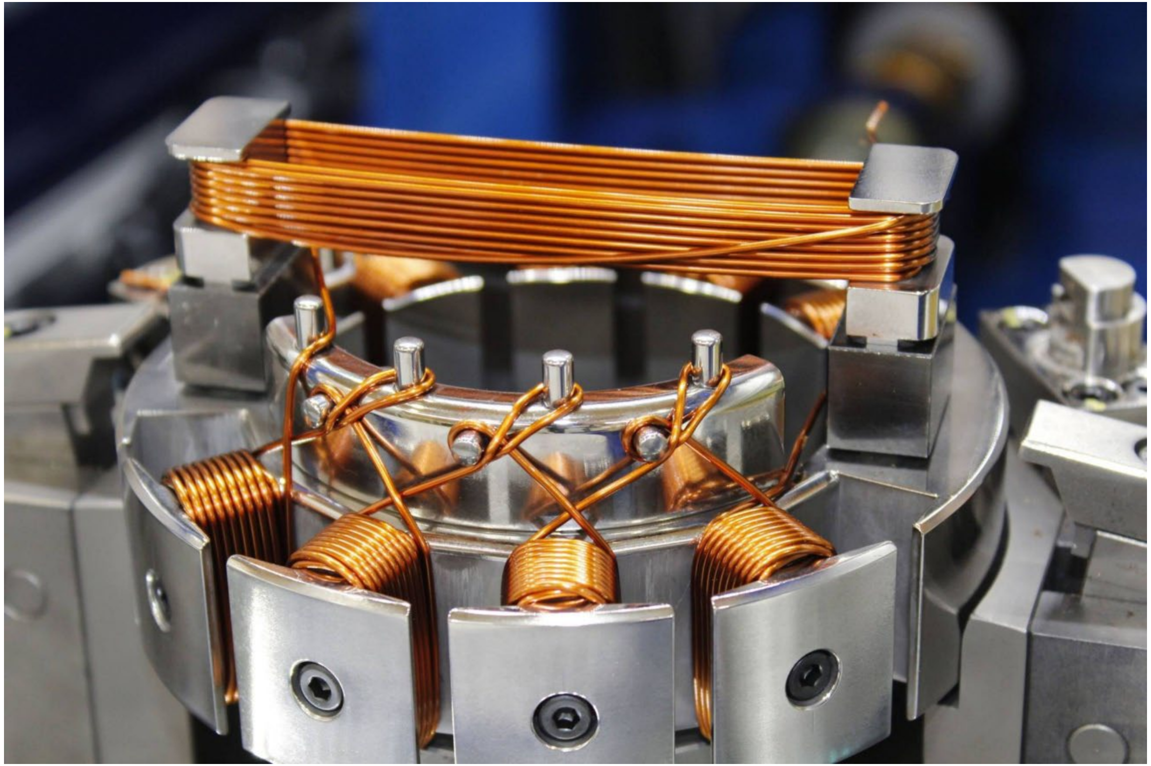
Determining the number of turns of the phase-coils

- Calculation of a number of turns window in conjunction with a drive

Thermal Analysis

- Mapping the limiting effects on machine design
- Thermal simulation in FEM (neglecting fluid-dynamical effects)

Number of turns calculation



Number of turns of the phase coils

The number of turns (N.O.T.) should be chosen such to be compatible with the electrical specifications of the drive over the intended range of operation

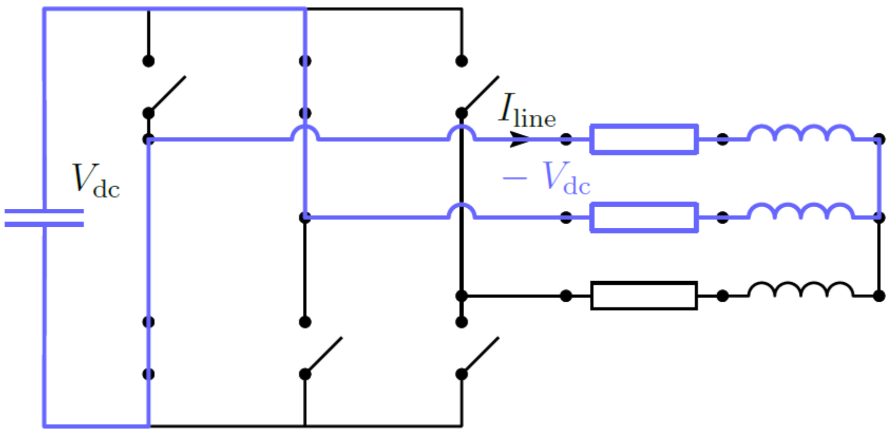
Create a basic machine model with the following properties

- The FEM model of the machine should contain only single turn coils
  - Calculate the phase-resistance of the single turn model: R_1
  - Determine/estimate the equivalent self/mutual inductance of the two-phase model: L_1 and M_{12}
  - Determine the flux of a single phase-coil as function of position: $\phi(\theta)$
- Determine the current-voltage rating of the drive
- Find the maximum speed, $\widehat{\omega}_{\mathrm{m}}$, at maximum torque of the machine

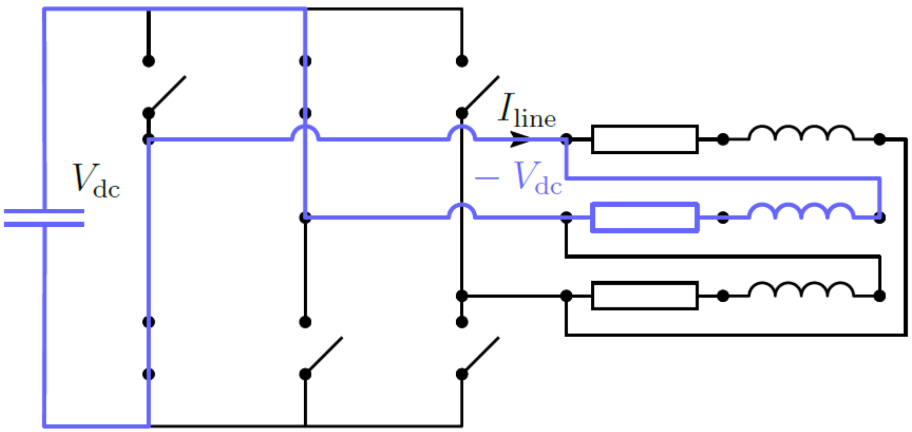
Number of turns of the phase coils

Machine connected to a power electronic PWM drive (See instruction week 5)

Wye-connection



Delta-connection



Number of turns of the phase coils

The phase voltage equation forms the basis of the N.O.T., *N*, calculation

$$V_{\mathrm{Un}} = I_{\mathrm{U}}(N)R_{\mathrm{ph}}(N) + L(N)\frac{\mathrm{d}I_{\mathrm{U}}(N)}{\mathrm{d}t} + M(N)\frac{\mathrm{d}I_{\mathrm{V}}(N)}{\mathrm{d}t} + \hat{\omega}_{\mathrm{m}}\underbrace{\frac{\mathrm{d}\Psi_{\mathrm{U}}(N,\theta_{\mathrm{m}})}{\mathrm{d}\theta_{\mathrm{m}}}}_{N\mathcal{E}_{\mathrm{U}}(\theta_{\mathrm{m}})}$$

In which

$$R_{\mathrm{ph}}(N) = N^2 R_1 = N^2 \overbrace{\frac{\rho\ell}{k_{\mathrm{f}}A_{\mathrm{slot}}}}^{R_1} \qquad I_{\mathrm{U}}(N) = \frac{\mathcal{F}_{\mathrm{U}}}{N}$$

$$L(N) = N^2 L_1 \qquad I_{\mathrm{V}}(N) = \frac{\mathcal{F}_{\mathrm{V}}}{N}$$

$$M(N) = N^2 M_{12} \qquad \Psi_{\mathrm{U}}(N,\theta_{\mathrm{m}}) = N\phi_{\mathrm{U}}(\theta_{\mathrm{m}}) \Rightarrow \mathcal{E}_{\mathrm{U}}(\theta_{\mathrm{m}}) = \frac{\mathrm{d}\phi_{\mathrm{U}}(\theta_{\mathrm{m}})}{\mathrm{d}\theta_{\mathrm{m}}}$$

Number of turns of the phase coils

The phase voltage scales with the N.O.T.:

$$V_{\mathrm{Un}} = N\left[\mathcal{F}_{\mathrm{U}} R_1 + \hat{\omega}_{\mathrm{m}}\left(L_1 \frac{\mathrm{d}\mathcal{F}_{\mathrm{U}}}{\mathrm{d}\theta_{\mathrm{m}}} + M_{12}\frac{\mathrm{d}\mathcal{F}_{\mathrm{V}}}{\mathrm{d}\theta_{\mathrm{m}}} + \frac{\mathrm{d}\phi_{\mathrm{U}}}{\mathrm{d}\theta_{\mathrm{m}}}\right)\right]$$

Other phase voltages are only phase-shifted

$$V_{\mathrm{Vn}}\left(\theta_{\mathrm{m}}\right) = V_{\mathrm{Un}}\left(\theta_{\mathrm{m}} - \frac{2\pi}{3N_{\mathrm{pp}}}\right), \qquad V_{\mathrm{Wn}}\left(\theta_{\mathrm{m}}\right) = V_{\mathrm{Un}}\left(\theta_{\mathrm{m}} + \frac{2\pi}{3N_{\mathrm{pp}}}\right)$$

Line voltages

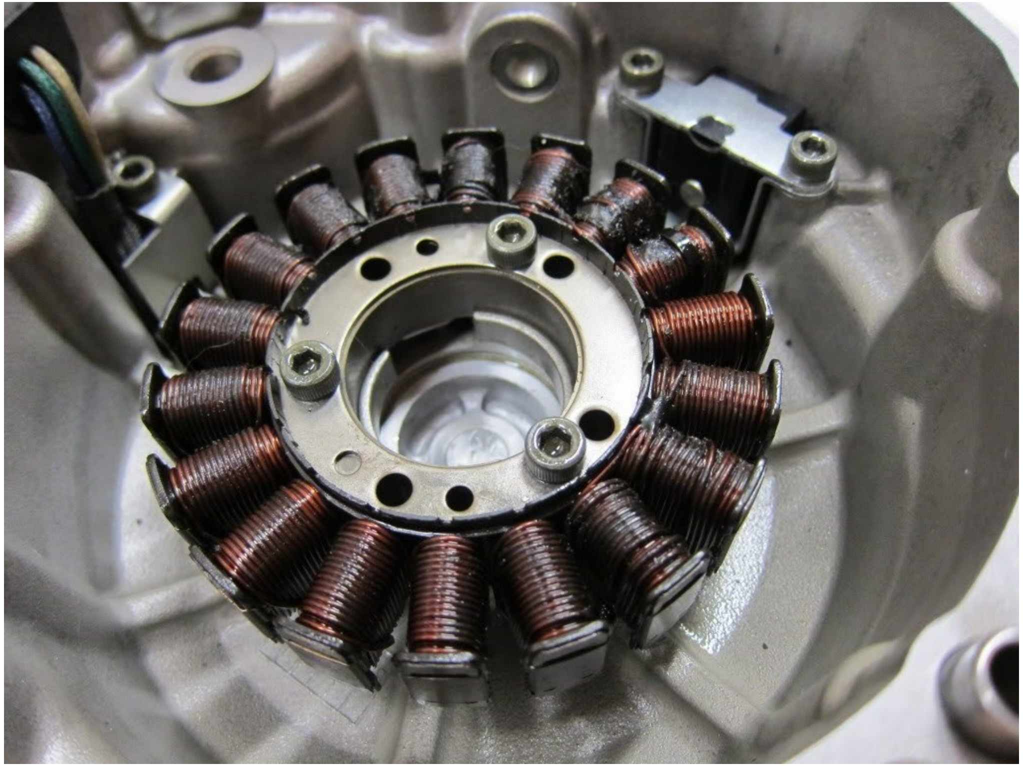
$$V_{\mathrm{UV}} = V_{\mathrm{Un}} - V_{\mathrm{Vn}}, \qquad V_{\mathrm{VW}} = V_{\mathrm{Vn}} - V_{\mathrm{Wn}}, \qquad V_{\mathrm{WU}} = V_{\mathrm{Wn}} - V_{\mathrm{Un}}$$

Number of turns of the phase coils

Values for voltages and currents follow from power-electronic drive specification

- Motor connection type in conjunction with DC-bus voltage and modulation index, *m,* determines speed limitation at given torque
  - **upper limit of N.O.T.**
  - Wye-connection: $\hat{V}_{\mathrm{line}} < mV_{\mathrm{bus}}$
  - Delta-connection: $\hat{V}_{\mathrm{phase}} < mV_{\mathrm{bus}}$
- RMS current limitations of the power-electronic drive determines the machine MMF
  - **lower limit of N.O.T.**
  - $I_{\mathrm{line}} < I_{\mathrm{drive}}$
- Within the N.O.T.-window all integer value are feasible
  - If possible, choose the value for the highest attainable filling factor, i.e. lowest phase resistance

Thermal analysis



Thermal limitations

Losses in machines lead to heat generation

- Excessive temperatures lead to damage or changes in material properties
  - Changes in electric resistances (affect both core and copper losses!)
  - Demagnetization effects
  - Insulation properties
  - Expansion phenomena
    - Mechanical stresses on bearings
    - Tolerances change with respect to manufacturing tolerances assumed during design/assembly
- Proper heat removal necessary to limit negative effects
- The spatial temperature distribution has to be known to determine hot spots

Thermal simulations

FLUX2D comes with an integrated heat-transfer simulation module

- Thermal ***conduction*** in ***stationary*** media (Fourier's law) within domain
  - Liquids and gasses at **standstill**
- Heat source regions in media within the domain
- Heat removal only on the boundary of the domain through
  - Simplified, equivalent convection coefficient
  - Thermal radiation
- Computational Fluid Dynamics (CFD) is ***not*** included in this module. CFD:
  - Fluid media, i.e. convection due to fluids (gasses and liquids) in **motion** ***is*** included
  - Navier-Stokes equations→ more accurate → computationally expensive and highly specialized software and knowledge required

Thermal simulations

The heat transfer problems are also defined by a parabolic PDE:

$$\left(\nabla \cdot [\kappa \nabla] - C_{\mathrm{V}} \frac{\mathrm{d}}{\mathrm{d}t}\right) T(x,y,t) = -q(x,y,t)$$

$$\left(\nabla \cdot [\nu \nabla] + \sigma \frac{\mathrm{d}}{\mathrm{d}t}\right) A_z(x,y,t) = -J_z(x,y,t)$$

Where

- T: temperature in [K]
- q: power volume density in [W/m^3]
- κ: thermal conductivity in [W/m/K]
- C_V: Volumetric heat capacity in [J/m^3/K]

Thermal simulations (steady state conditions)

Poisson equation for steady–state (same as the magnetostatic formulation: elliptic)

$$\nabla^2 T(x,y) = -\frac{1}{\kappa} q(x,y) \qquad \left(\nabla^2 A_z(x,y) = -\mu_0 \mu_r J_z(x,y)\right)$$

Heat flux density [Wm^{-2}]: $\vec{q}(x,y) = -\kappa \nabla T(x,y)$

Heat removal at boundaries of regions lead to Neumann boundary conditions

- Convection through boundary surface: $\vec{q} \cdot \vec{n} = -h_\mathrm{c} \left(T - T_\mathrm{amb}\right)$
- Thermal radiation via boundary surface: $\vec{q} \cdot \vec{n} = -\varepsilon\sigma \left(T^4 - T_\mathrm{amb}^4\right)$
  - h_c: convection coefficient in [W/m^2/K]
  - ε: emissivity (ε=1 for a black body)
  - σ: Stephan-Boltzmann-constant $5.67 \cdot 10^{-8}$ W/m^2/K^4
  - T_amb: ambient temperature in [K]

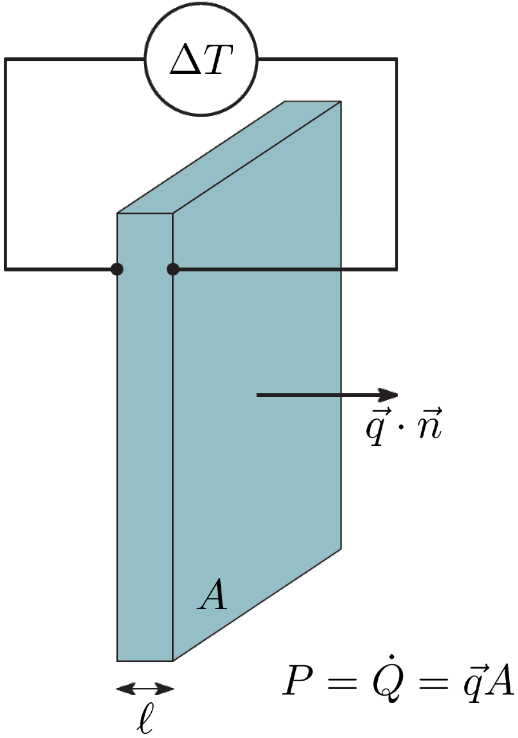
Transport of thermal energy through conduction

Heat is generated in the coils due to copper losses

- Temperature gradient causes thermal energy to flow:
  - From turn to turn
  - From copper to insulation, to air, to insulation to copper ...
  - From slot liner to core material
  - From core to (housing to) ambient
- Thermal resistance (equivalent to resistance and reluctance)

$$R_{\text{th}} = \frac{\Delta T}{\dot{Q}} = \frac{\Delta T}{P} = \frac{\ell}{\kappa A} \quad \left[\frac{\text{K}}{\text{W}}\right]$$

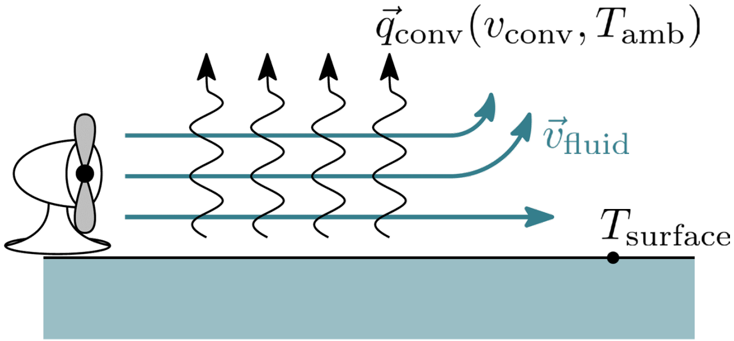
- ***<u>Effective</u>*** thermal conductivity of a coil, κ, equal to 1! *Why?*



Removal of thermal energy through convection

Heat is removed from the outer surface of the machine by convection on account on a fluid flowing across its surface: $\vec{q} \cdot \vec{n} = -h_\mathrm{c}\left(T - T_\mathrm{amb}\right)$

$$\begin{aligned} R_\mathrm{th} &= \frac{\Delta T}{\dot{Q}} = \frac{T - T_\mathrm{amb}}{A\vec{q} \cdot \vec{n}} \\ &= \frac{T_\mathrm{amb} - T}{-Ah_\mathrm{c}\left(T - T_\mathrm{amb}\right)} \\ &= \frac{1}{Ah_\mathrm{c}} \quad \left[\frac{\mathrm{K}}{\mathrm{W}}\right] \end{aligned}$$



Convection	h_c [W/m²K]
Free	
Gases	2 – 2.5
Liquids	50 - 1000
Forced	
Gases	25 – 250
Liquids	50 - 20000

Removal of thermal energy through radiation

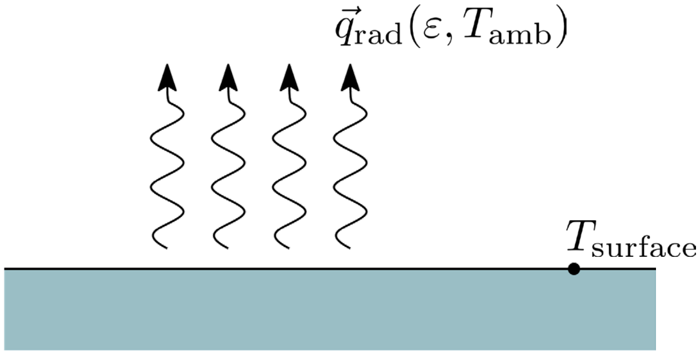
Heat removal by radiation: $\vec{q} \cdot \vec{n} = -\varepsilon\sigma \left(T^4 - T_{\mathrm{amb}}^4\right)$

- Linearization for small variations in temperature

$$R_{\mathrm{th}} = \frac{\Delta T}{\dot{Q}} = \frac{T - T_{\mathrm{amb}}}{A\vec{q} \cdot \vec{n}}$$
$$\approx \frac{1}{Ah_{\mathrm{r}}} \quad \left[\frac{\mathrm{K}}{\mathrm{W}}\right]$$

- $h_{\mathrm{r}} = 6\varepsilon$ at room temperature
  - Error of linearization for ΔT=100 K: 2-3%

- Only means of heat removal to the ambient in vacuum



Simplified thermal model for crude estimates

Heat removal through convection in the *radial* direction only and $\kappa \to \infty$

$$A = 2\pi r L$$

$$R = \frac{1}{A h_\mathrm{c}}$$

$$P_\mathrm{max} = \frac{T_\mathrm{max} - T_\mathrm{amb}}{R} = \underbrace{2\pi r L h_\mathrm{c}}_{\frac{1}{R}} \left(T_\mathrm{max} - T_\mathrm{amb}\right)$$