Motivation and aims:
The quality of coatings, produced by HVOF thermal spraying processes, considerably decreases with the rising degree of complexity of the geometry of components. Experimental analyses of project A2 suggest significant temperature excursions in the substrate in dependence of the component geometry, whereby the coating quality decreases due to residual stresses during the cooling process. To numerically capture the transient thermal field concerning complex component geometries, a thermodynamically consistent finite-element-framework for rigid non-linear heat conductors is implemented, where the energy flux by the HVOF spray gun is described by convective heat transfer by means of a film condition.

Methods:
In a first step, the governing equations of continuum thermodynamics are formulated for a rigid heat conductor and are, in a second step, discretised in a temperature-based finite-element scheme.

Step 1: Continuum thermodynamics

- Balance of energy
  \[ \rho \frac{\partial \theta}{\partial t} + \nabla \cdot (\rho \nabla \theta) = q \]
  \[ \text{Heat capacity} \]
  \[ c(\theta) = -\theta \frac{\partial^2 \theta}{\partial \theta^2} \]

- Clausius-Duhem inequality
  \[ \psi(\theta) \equiv \varphi(\theta) - \theta \eta(\theta) \]
  \[ \text{Free energy density} \]

- Specific balance of energy equation in strong form to be discretised in the finite-element-framework

Step 2: Finite element discretisation

Discretisation

- Spatial discretisation
  \[ \Delta \Omega \approx \Omega_h \]

- Time discretisation
  \[ \Delta t \]

Assume a cubic relation for the temperature \( c(\theta) = a_1 \theta^3 + a_2 \theta + a_3 \)

Calculate solution by iterative Newton-Raphson scheme:

\[ R_{\theta} = \frac{\partial R(\theta)}{\partial \theta} = 0 \]

\[ \theta_{n+1} = \theta_n - R(\theta) \left( K(\theta_n) \right)^{-1} \]

Elements

- tetrahedral
  \[ \Delta \Omega \approx \Omega_h \]
- triangular
  \[ \Delta \Omega \approx \Omega_h \]

Results:
The finite-element-framework is used to carry out test simulations. A complex geometry, as depicted in figure 1, is discretised by 1361 nodes spanning a mesh of 5751 tetrahedral volume elements. Here, the darkened surface is furthermore discretised by 60 triangular surface elements. These surface elements are time-dependently exposed to thermal load by the HVOF spray gun at 1273.15 K – powder spraying is not captured by this approach. The material parameters used are listed in table 1.

Fig. 1: Mesh with 1361 nodes, 5751 tetrahedral and 60 triangular elements.

Fig. 2: Temperature contour plot at (a) \( t = 0.5 \) s (b) \( t = 90 \) s (c) \( t = 180 \) s.

Fig. 3: Plot of the heat flux vectors at (a) \( t = 0.5 \) s (b) \( t = 90 \) s (c) \( t = 180 \) s.