Highly Integrated Heat Exchangers for Automotive Thermoelectric Generators (TEG)

Methodical functional integration and numerical analysis of TEG heat exchangers

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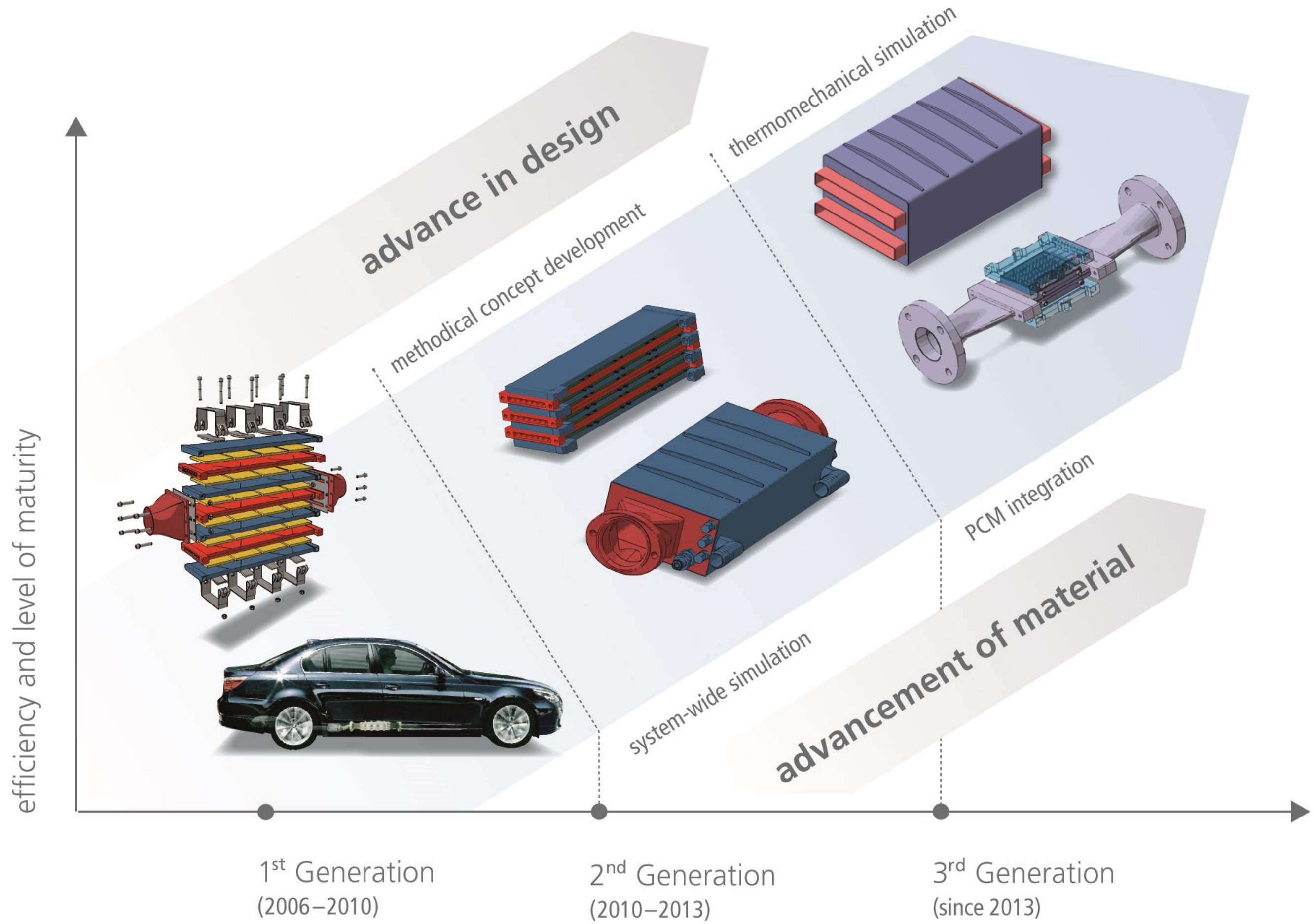
DLR

Outline

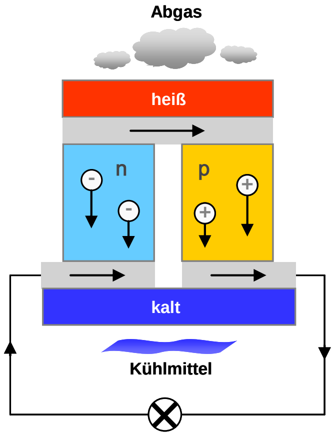
- Introduction
- Methodical concept development acc. to VDI Guideline 2221
- Module structure used for functional integration
- Comparison between three heat exchanger approaches
- Numerical and analytic analysis with focus on
  - Fin buckling
  - Reduction of thermomechanical stress
  - Homogenisation of contact pressure

Evolution of TEG at DLR

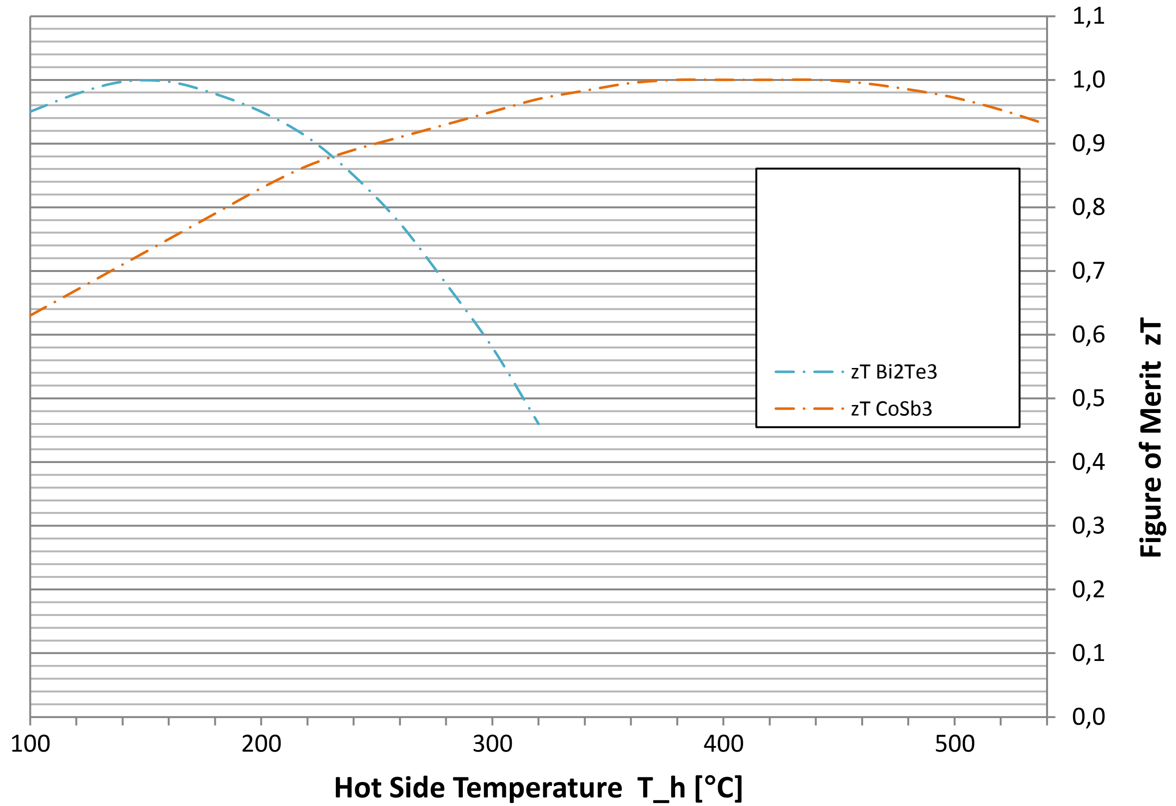


Introduction
Why use high temperature TE-Materials?

- Comparison between Bithmuth Telluride and Skutterudite
- Exemplarily Materials with $zT_{max} = 1$



$$U = S \cdot \Delta T$$



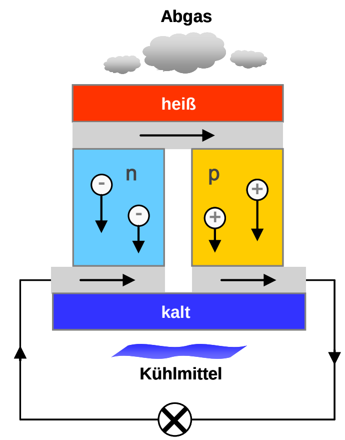
$$zT = \frac{S^2 * \sigma}{\kappa} * T$$

$$\eta_{\mathrm{max}} = \eta_{\mathrm{Carnot}} * \eta_{\mathrm{ex}}$$

$$\eta_{\mathrm{Carnot}} = \frac{T_{\mathrm{h}} - T_{\mathrm{c}}}{T_{\mathrm{h}}}$$

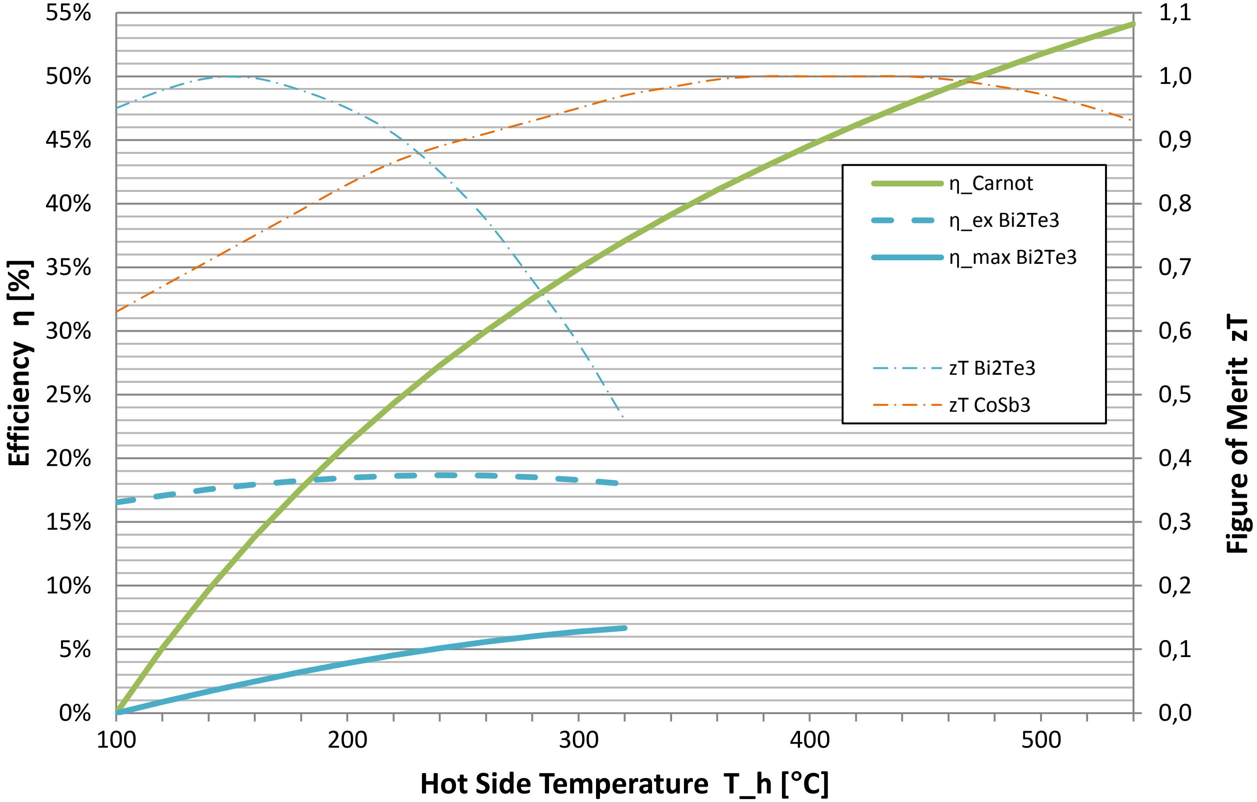
$$\eta_{\mathrm{ex}} = \frac{\sqrt{1 + zT_m} - 1}{\sqrt{1 + zT_m} + T_{\mathrm{c}}/T_{\mathrm{h}}}$$

Introduction
Why use high temperature TE-Materials?



$$U = S \cdot \Delta T$$

- Higher efficiency at high temperatures mainly through higher Carnot efficiency
- zTmax=1 leads to an exergy efficiency η_{ex} ~ 17%



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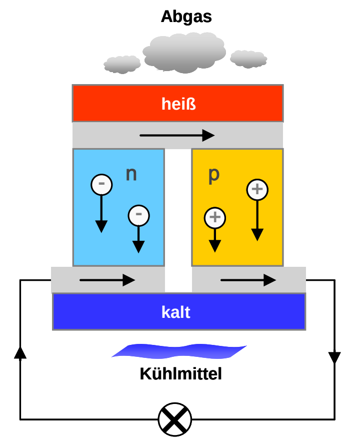
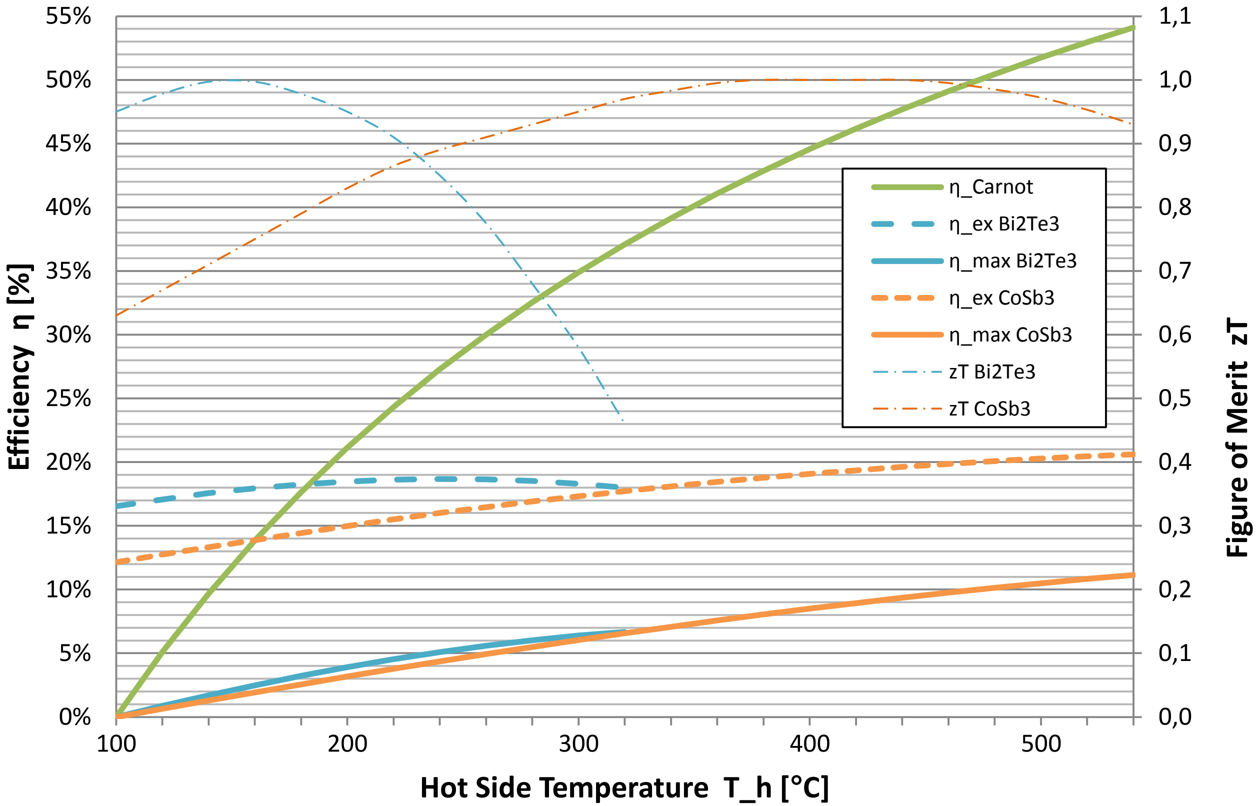
Cold Side Temperature T_c = 100°C

Introduction
Why use high temperature TE-Materials?



$$U = S \cdot \Delta T$$

- Higher efficiency at high temperatures mainly through higher Carnot efficiency
- zTmax=1 leads to an exergy efficiency $\eta_{\mathrm{ex}} \sim 17\%$



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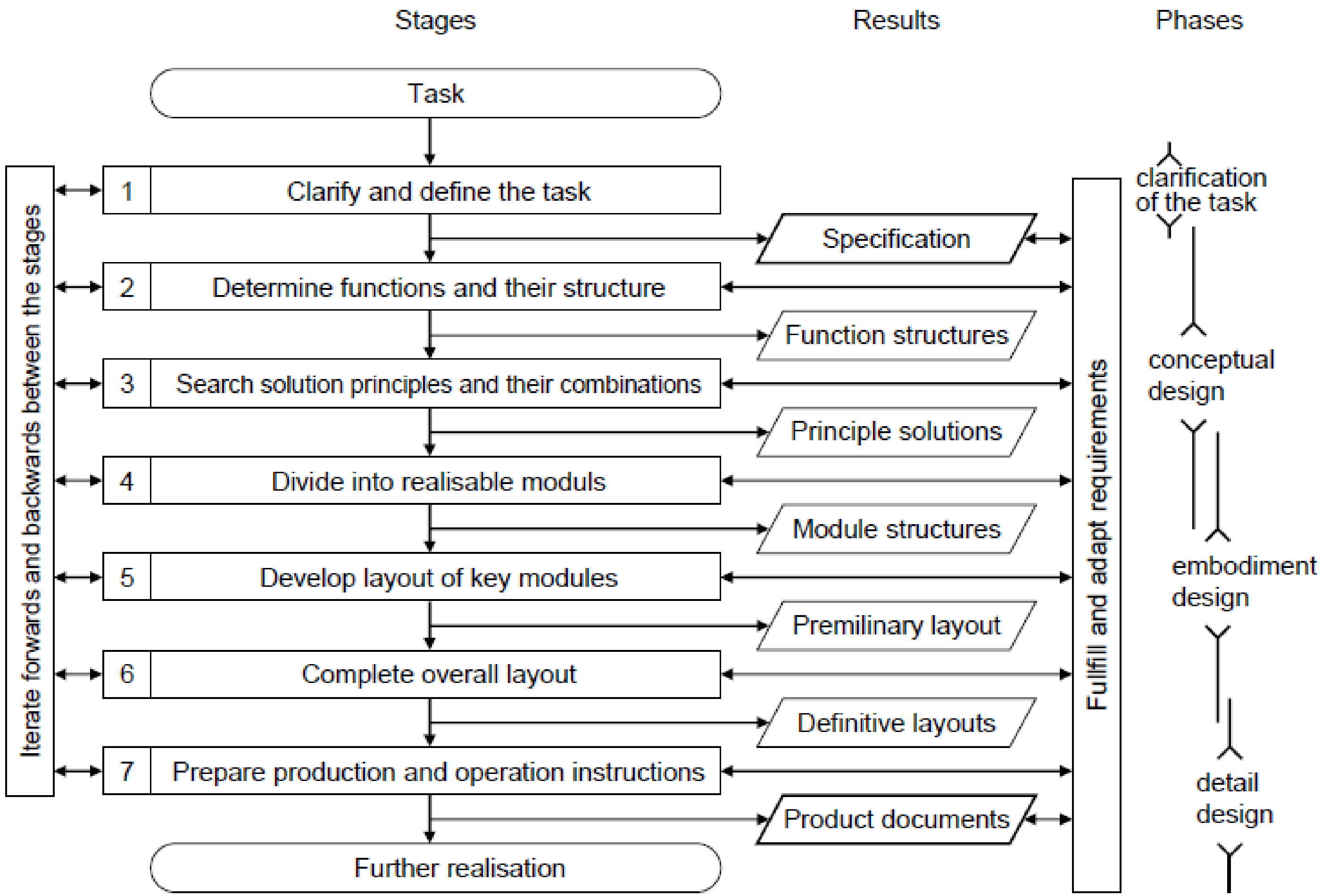
Cold Side Temperature T_c = 100°C

Procedural method

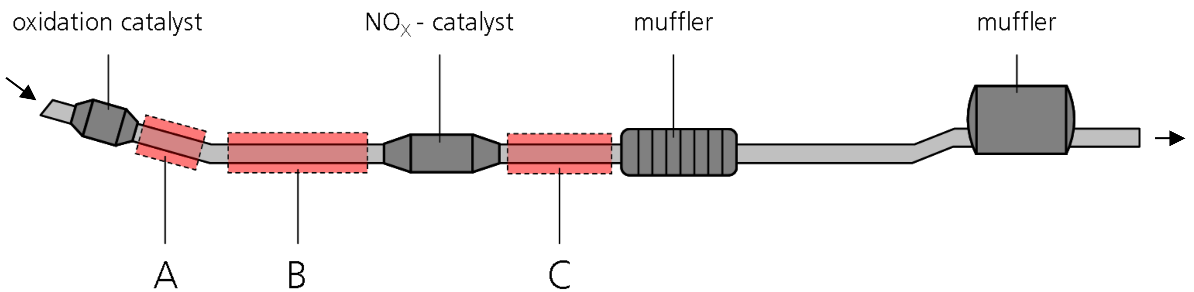
VDI Guideline 2221



List of requirements
e.g. Vehicle boundary conditions

DLR – test vehicle

- BMW 535i
- 3l, 6 cylinder, spark ignition
- 190kW @ 6600 1/min

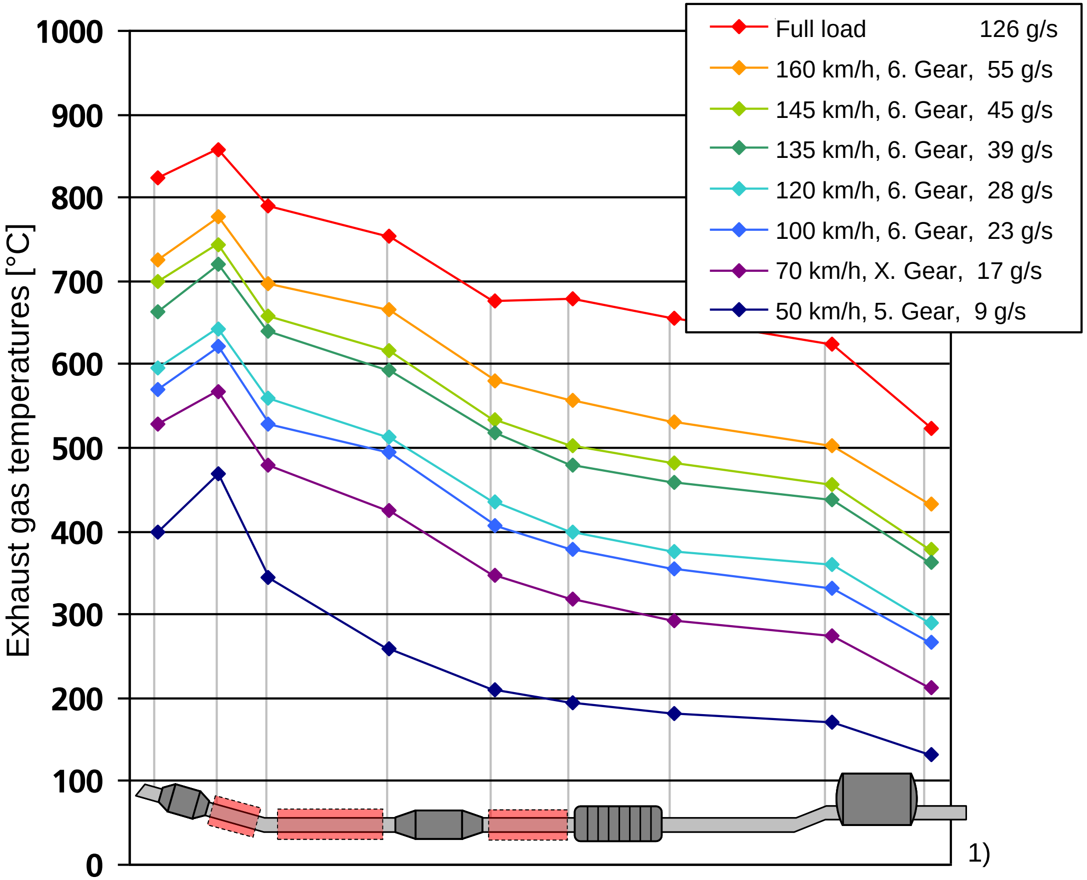


	A	B	C
installation space			
length	210mm	400mm	440mm
width	290mm	170mm	270mm
height	190mm	150mm	170mm

1) Kober, M. ; Häfele, C. ; Friedrich, H. E. (2012) Methodical Concept Development of Automotive Thermoelectric Generators (TEG). 3. International Conference 'Thermoelecrics goes Automotive', 2012, Berlin, Deutschland.

List of requirements

e.g. Gas temperatures along exhaust system



- Gas temperatures along exhaust system at different steady state driving conditions with replaced NO_x-catalyst.

1) Kober, M. ; Häfele, C. ; Friedrich, H. E. (2012) Methodical Concept Development of Automotive Thermoelectric Generators (TEG). 3. International Conference 'Thermoelecrics goes Automotive', 2012, Berlin, Deutschland.

Interactions of TEG and vehicle system

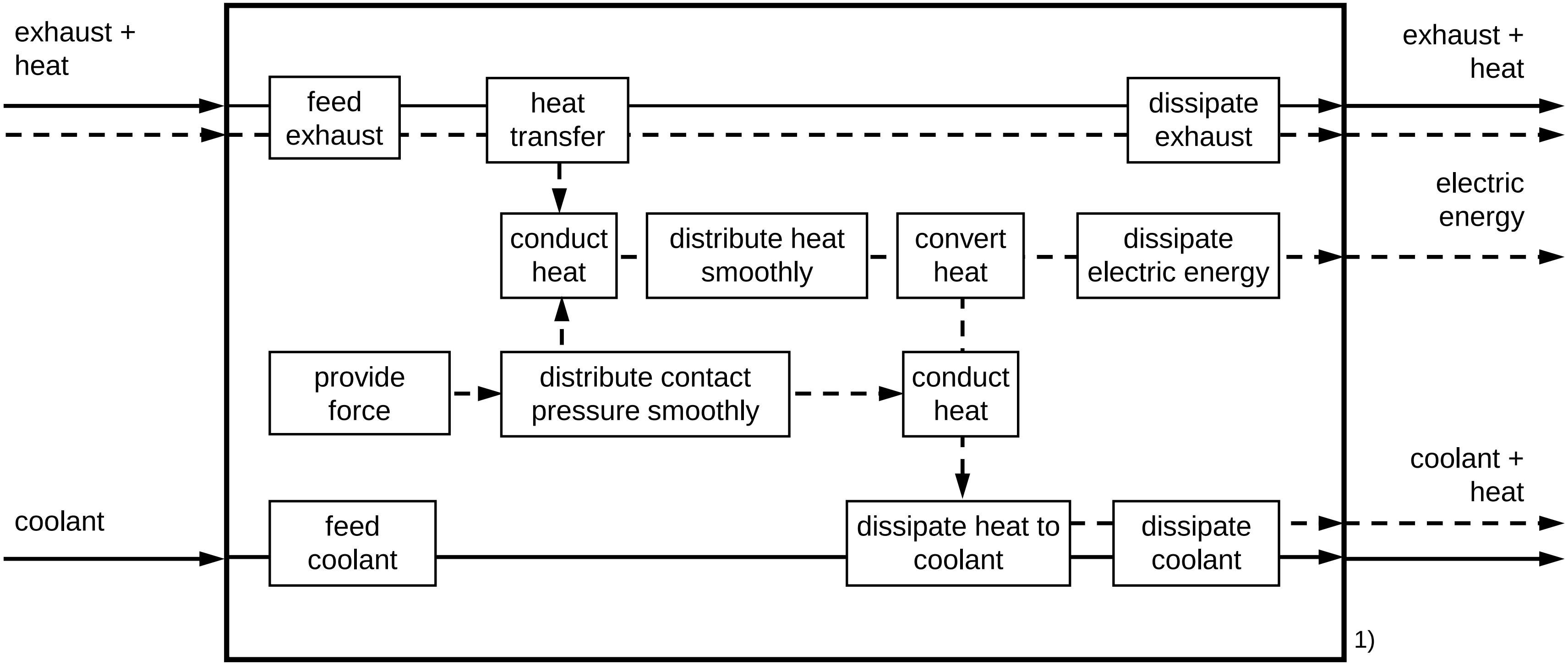
electrical TEG input power
(ΔP_{in})

cooling load (ΔP_{co})
(el. power for cooling water pump and cooling fan)

back pressure / cooling of exhaust
(ΔP_{pr})

rolling resistance (ΔP_{ro})
(weight increase)

TEG concept development – Function structure



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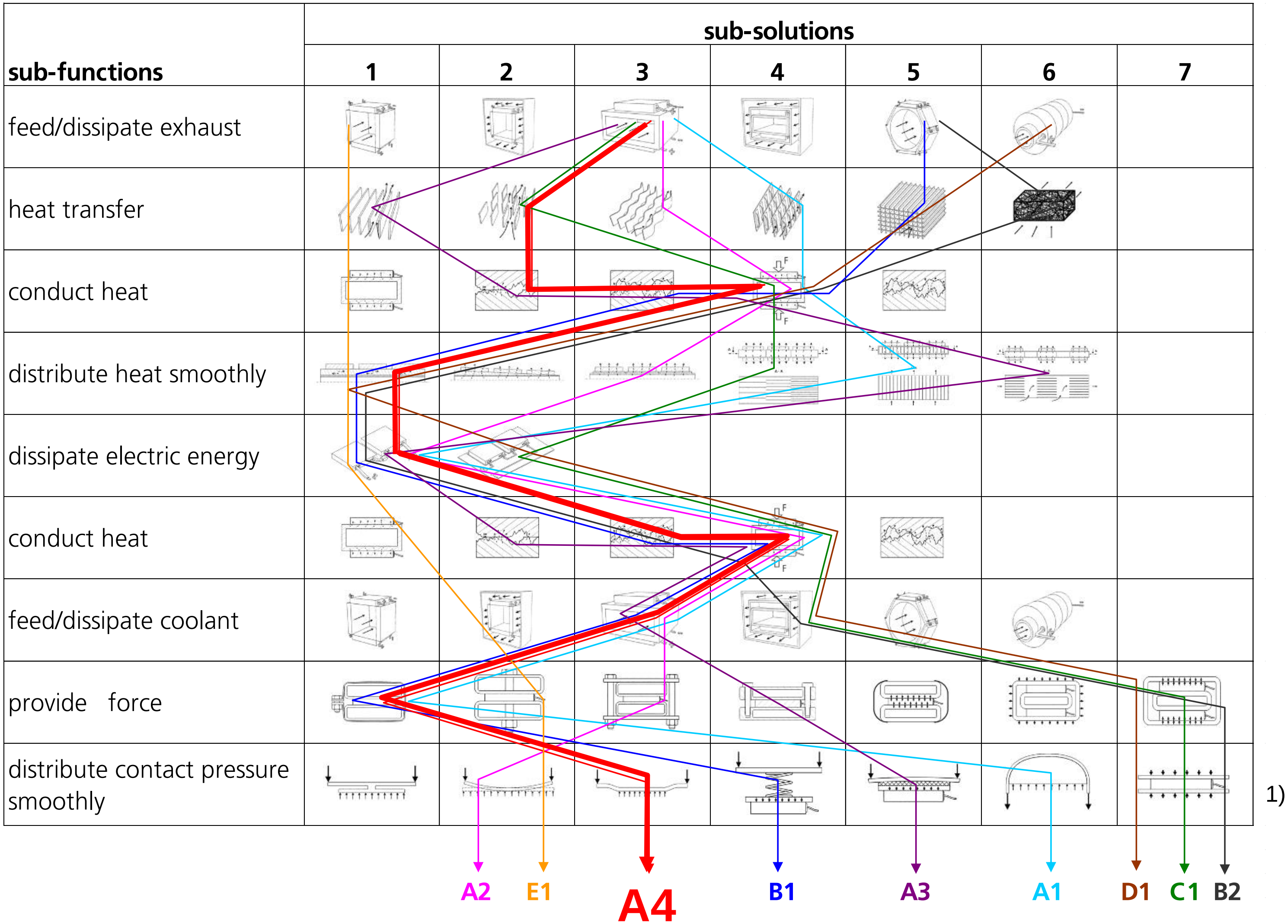
TEG concept development – Sub-solutions



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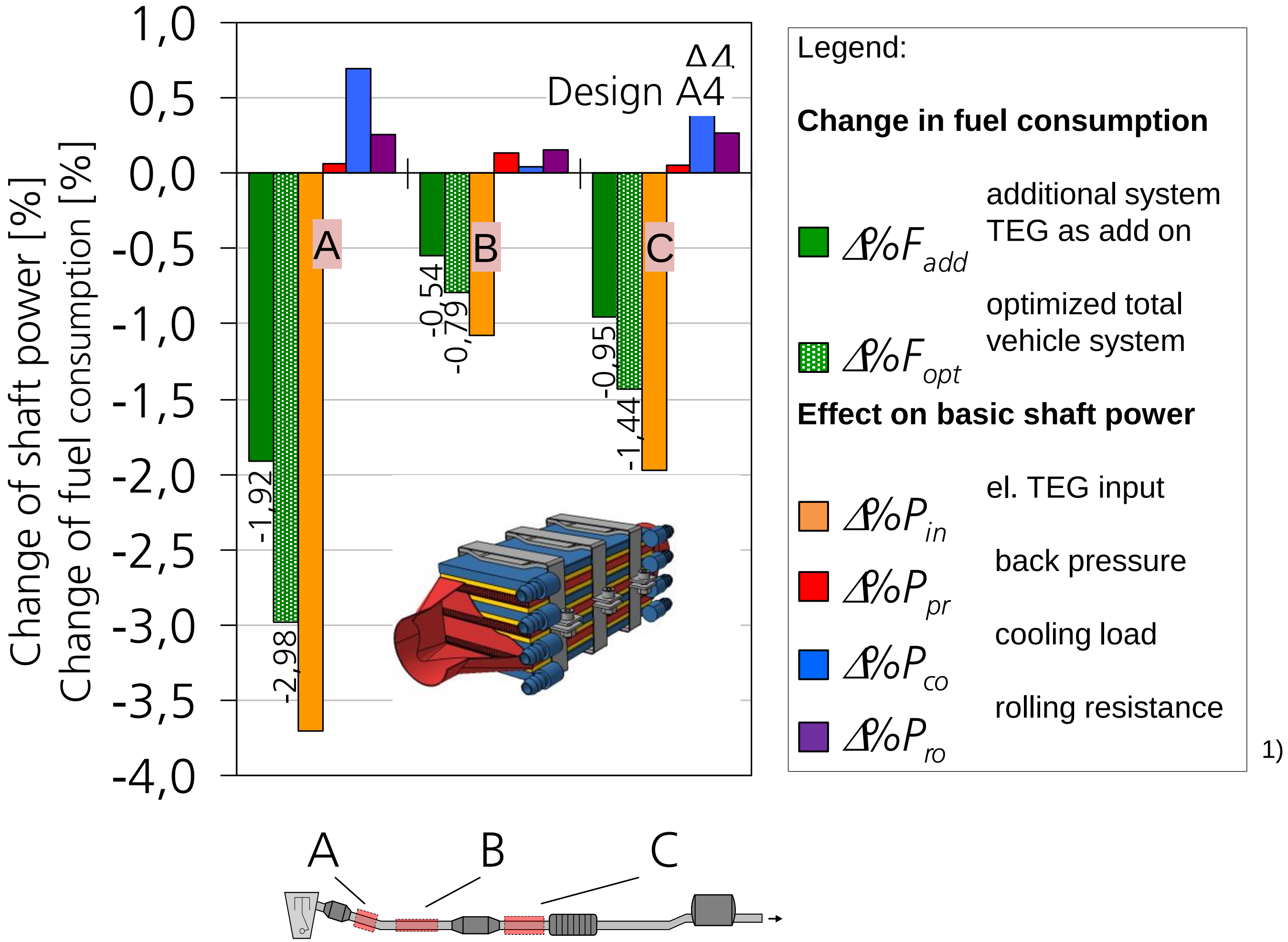
Overall system simulations

Results for design point 135 km/h



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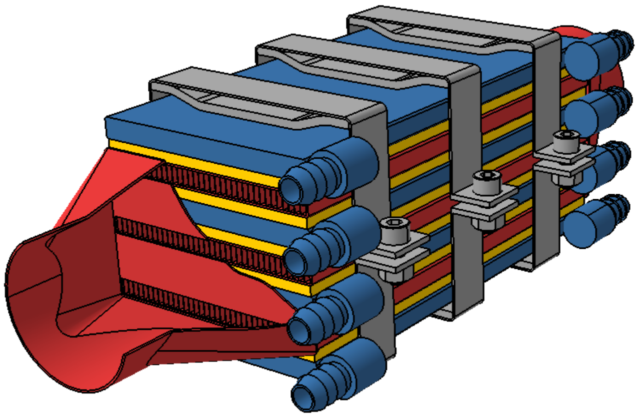
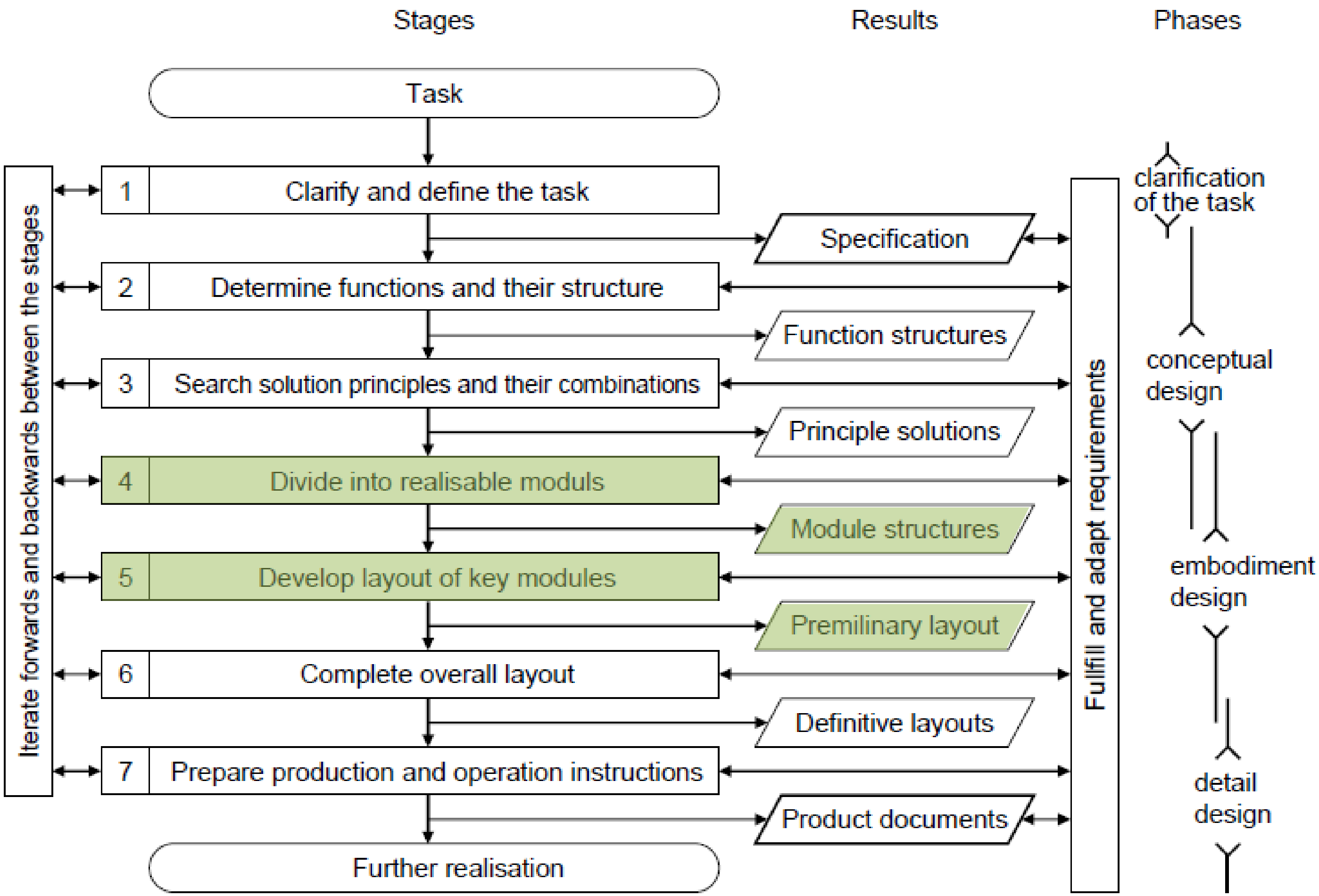
How can functional integration be done to reduce the TEG weight and thermomechanical stress?

? ?



Module structure (acc. to VDI 2221) for functional integration within heat exchangers



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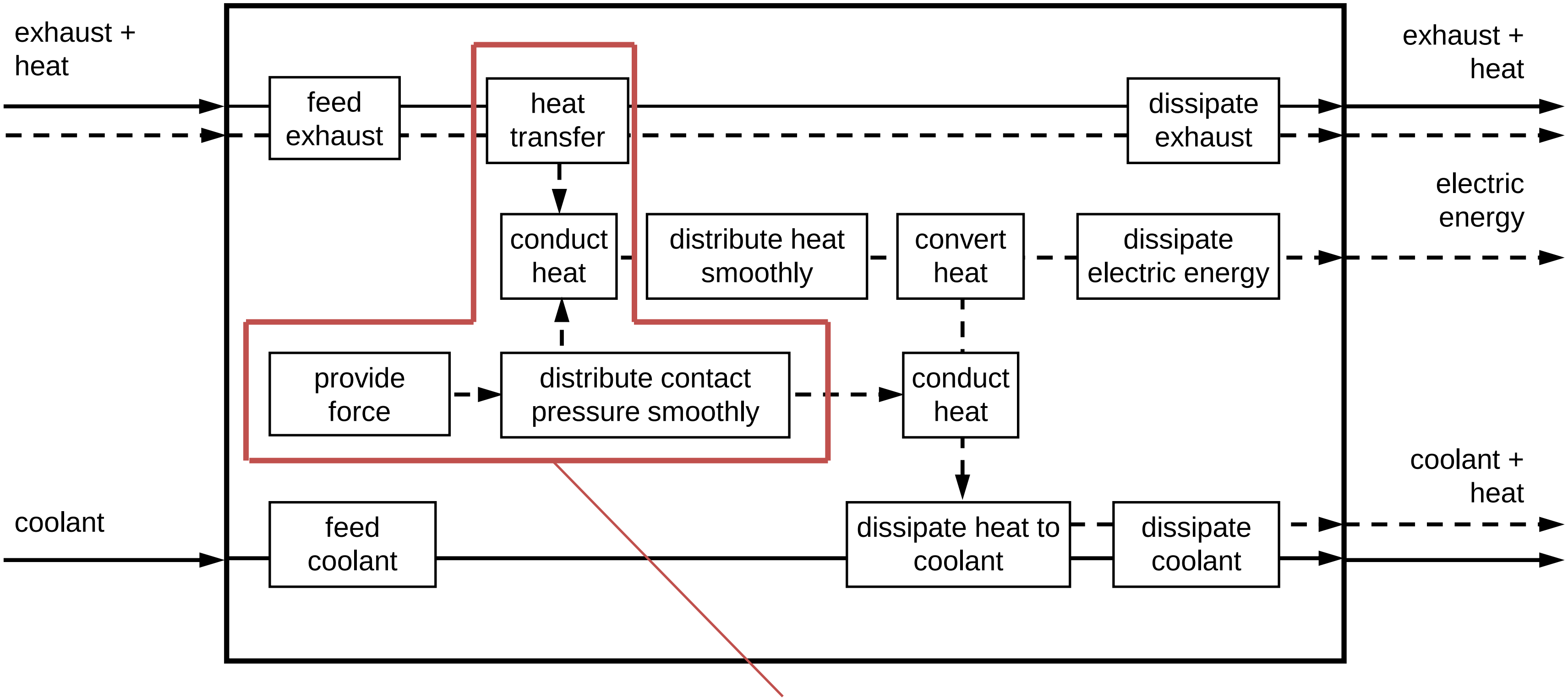
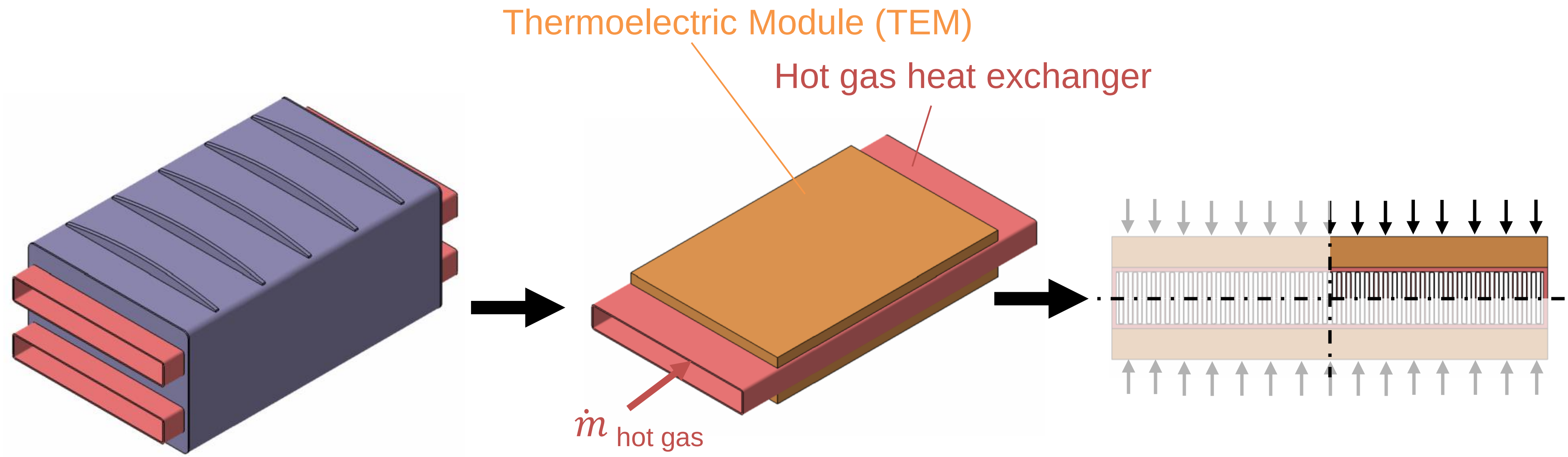


functional integration of thermal and mechanical functions within the hot gas heat exchanger

Module structure
Hot gas heat exchanger



Thermoelectric Generator (TEG)

Module structure
(acc. VDI Guideline 2221)
Hot gas heat exchanger

2D - Simulation model
Hot gas heat exchanger
with TEM

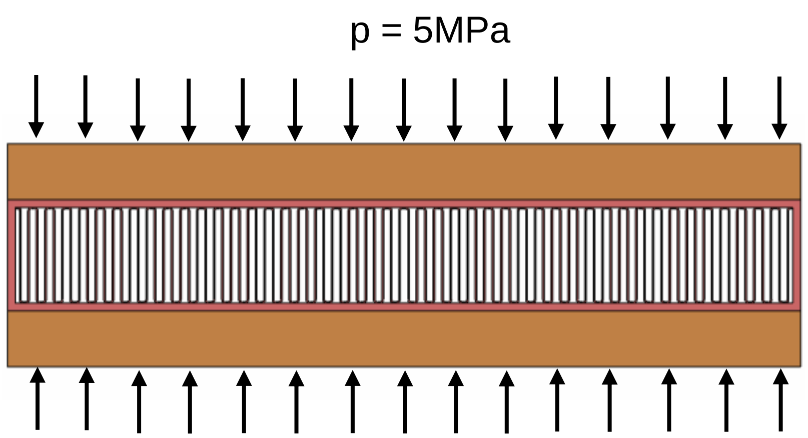
Analytic analysis of fin buckling

- buckling formulation:

$$F = \frac{\pi^2 * E * I}{L^2} \quad -> \quad p = \frac{\pi^2 * E * I}{L^2 * A}$$

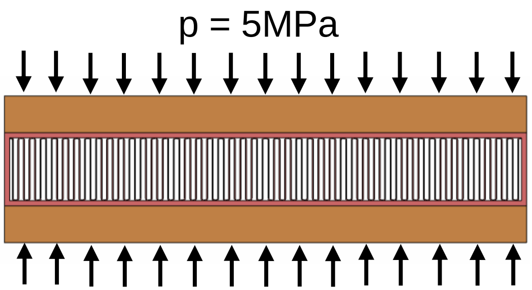
factor of safety s = 3

analytic pressure p = 5 MPa



- Variation of
  - fin distance
  - fin thickness
  - heat exchanger height (fin leght)

Analytic analysis of fin buckling



Compromises for functional integration between

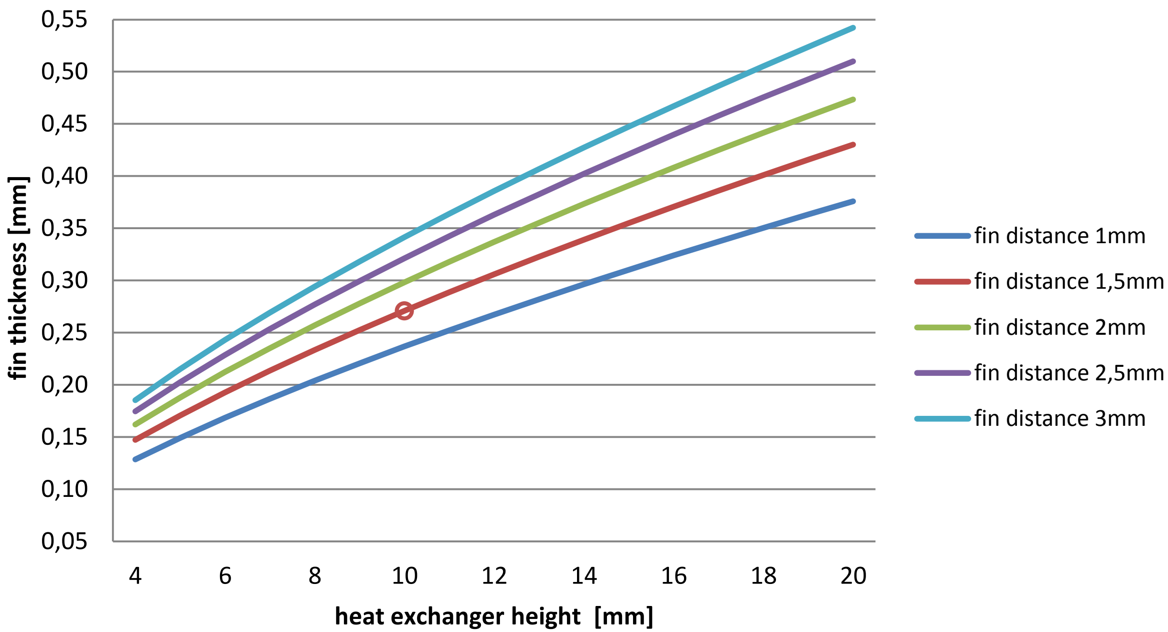
thermal and mechanical functions are too high

- Thermal functions:

  thin fins required

- Mechanical functions:

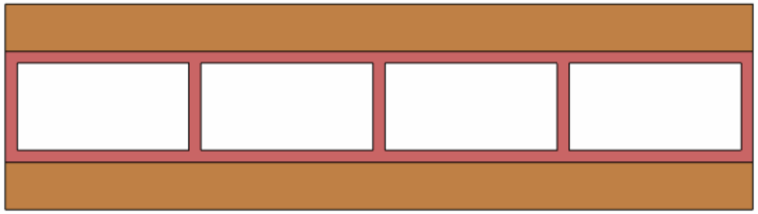
  thick fins required



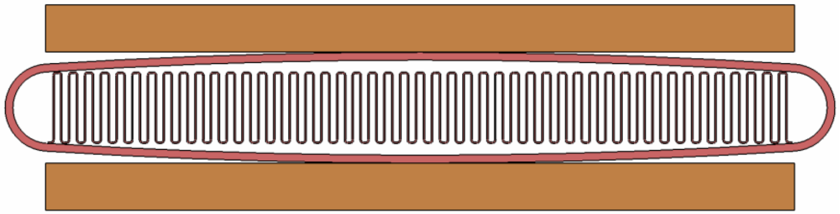
Approaches

- Homogenisation of contact pressure
- Reduction of thermomechanical stress at thermoelectric modules (TEM)
- Integration of thermal and mechanical functions within the heat exchanger fins

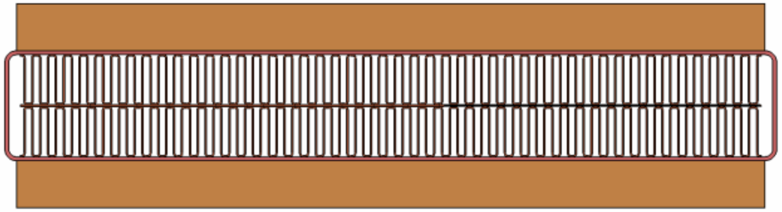
1.) Design with Reinforcements 1)



2.) Oval Design 2)



3.) Functional Integration



(Two or more levels of fins – Approach of this work)

1) Patent: DE102010042603 A1
2) Bürkle, A. ; et al. : Numerical optimisation of contact pressure with respect to the heat exchange properties of a thermo-electric generator. 2. International Conference 'Thermoelecrics goes Automotive', 2010, Berlin, Deutschland.

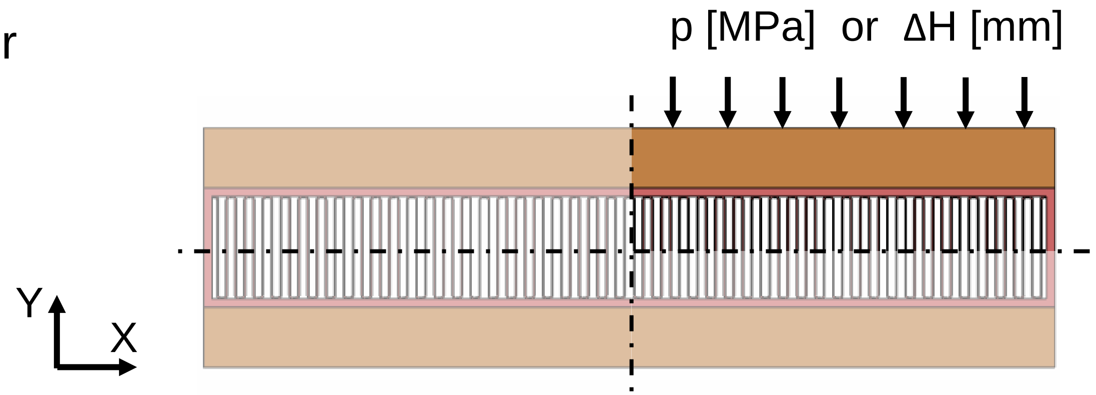
Numerical Analysis

Procedure

- Quarter of a heat exchanger module structure is simulated
- Symmetry in x- and y-direction
- Constant pressure or deformation load

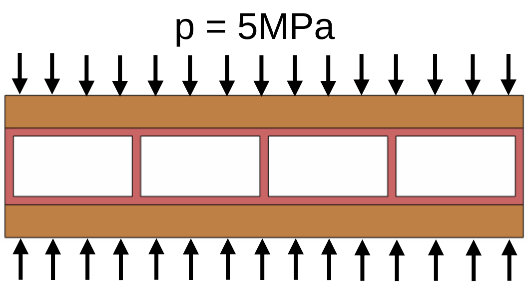
Goals

- Avoidance of fin buckling
- Homogeneous contact pressure
- Min. contact pressure of 1MPa
- Low mechanical stress at the TEM



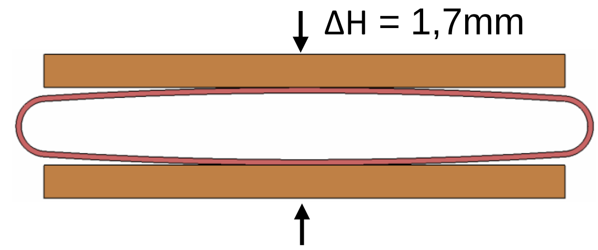
Results - Design with Reinforcements

- Result: Inhomogeneous contact pressure
  Contact pressure < 1 MPa
  High local stress at TEM



Results - Oval Design

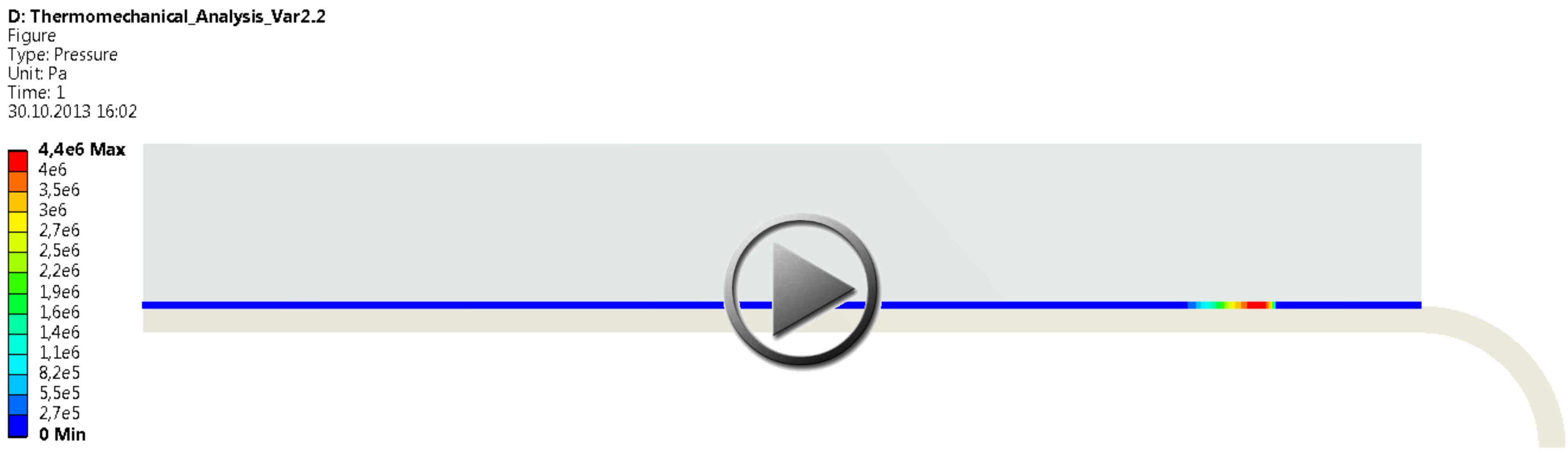
- Fins do not homogenise the contact pressure significantly by reason of buckling
  - ➢ Analysis simplification: modeling without fins



- Result: Inhomogeneous contact pressure

  Contact pressure < 1 MPa

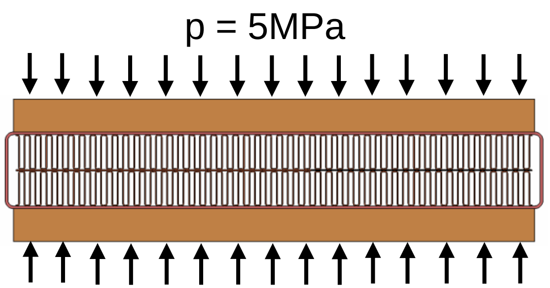
  High local stress at TEM



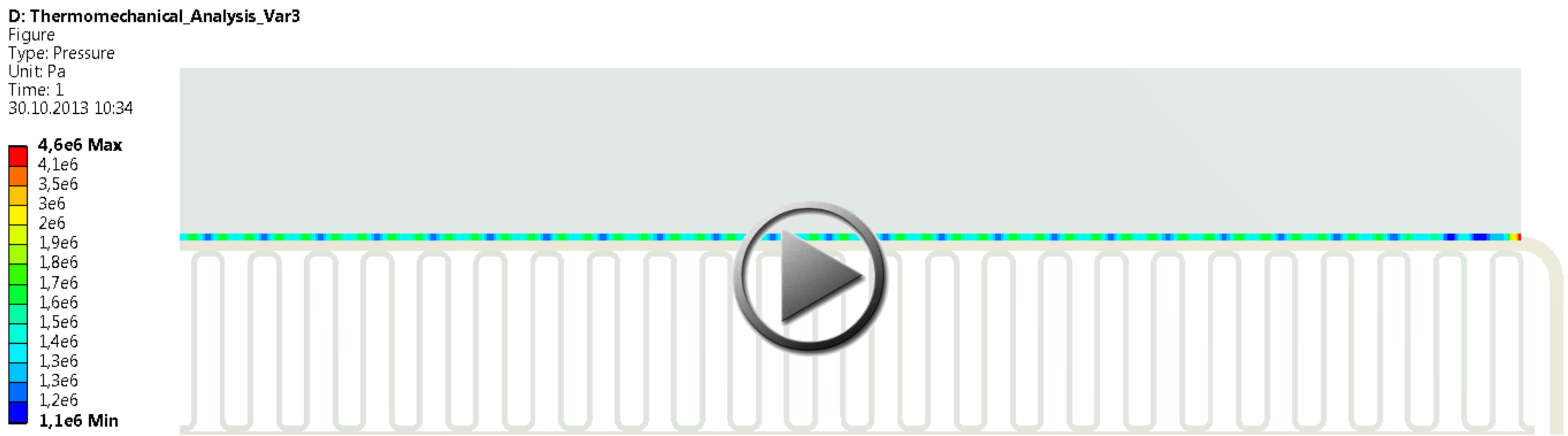
DLR

Results - Functional Integration

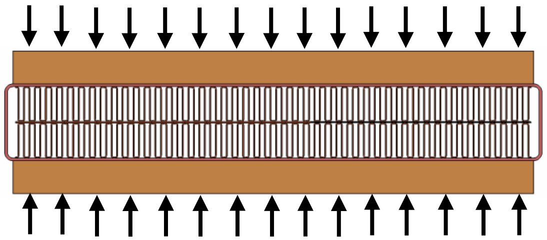
- Reduction of fin length through two fin layers
  - ➢ Thermal and machanical functions integrated within the fins without functional compromises



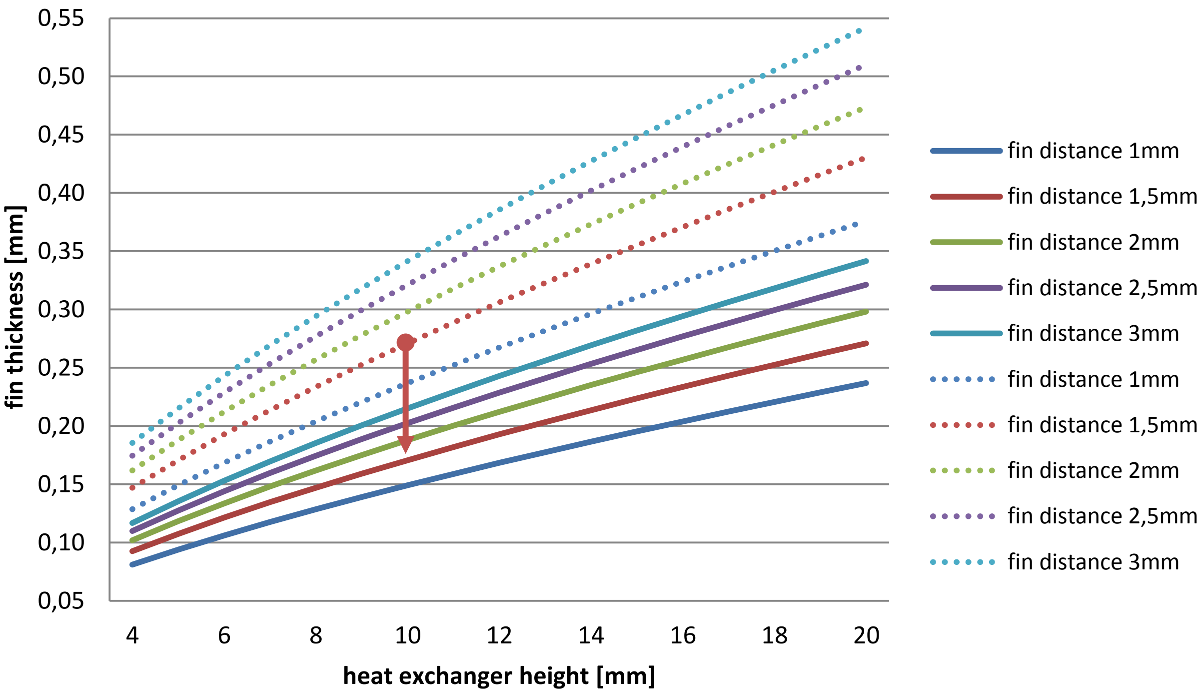
- Result: Homogeneous contact pressure
  Contact pressure > 1 MPa
  Low stress at TEM



Analytic analysis of fin buckling in multilayer fin structures

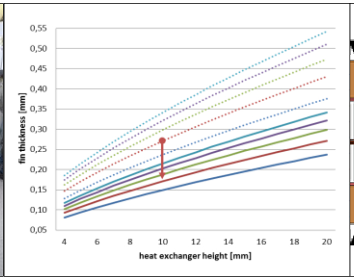


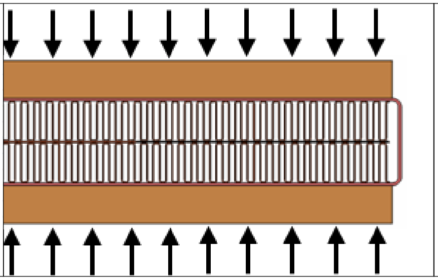
- Required fin thickness in a two layer fin structure:

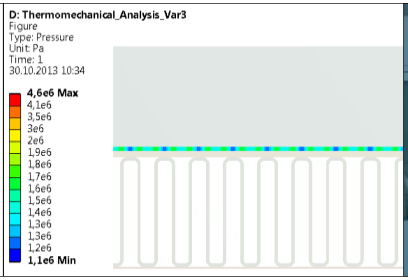


Summary

- Functional integration by using the module structure of VDI Guidline 2221
- Comparison of three approaches to homogenise contact pressure
- Multilayer fins is the only approach that achieve the requirements:
  - Homogeneous contact pressure
  - Low mechanical stress at TEM
- Successful integration of thermal/mechanical functions within heat exchanger







Acknowledgement

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Baden-Württemberg
MINISTERIUM FÜR FINANZEN UND WIRTSCHAFT

Thank you for your attention!

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