mechanical integrity of PFHE in LNG liquefaction process

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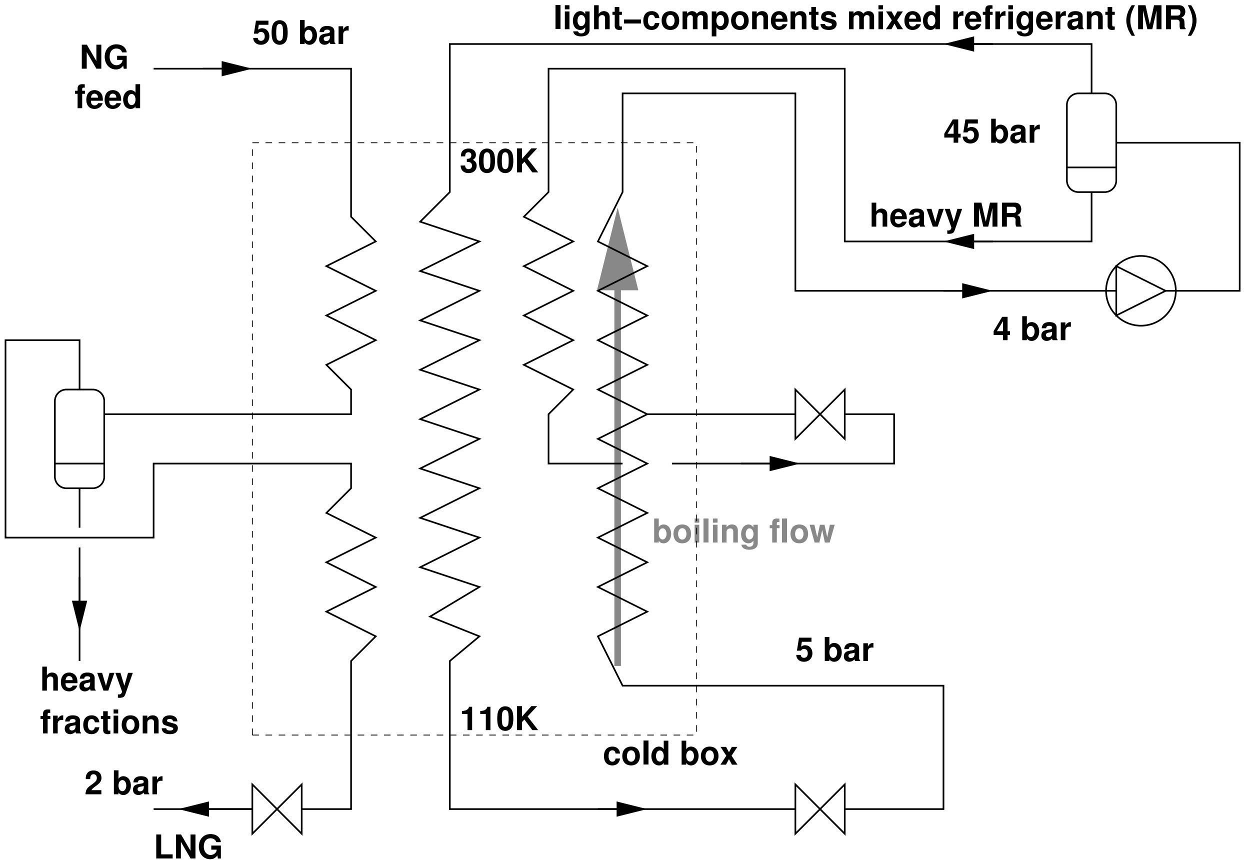
temperature, boiling flow, thermal stresses

multi-domain simulation problem

- component mixtures
- vapor pressure
- multiphase flow*
- boiling flows
- heat exchange*
- flow pulsations*
- mechanical integrity*
- thermal stresses

* core expertise of the Fluid Dynamics group at TNO in Delft

knowledge investment programme at TNO,
to cover all aspects of boiling heat exchanger



multiple streams: NG, MR

different pressures

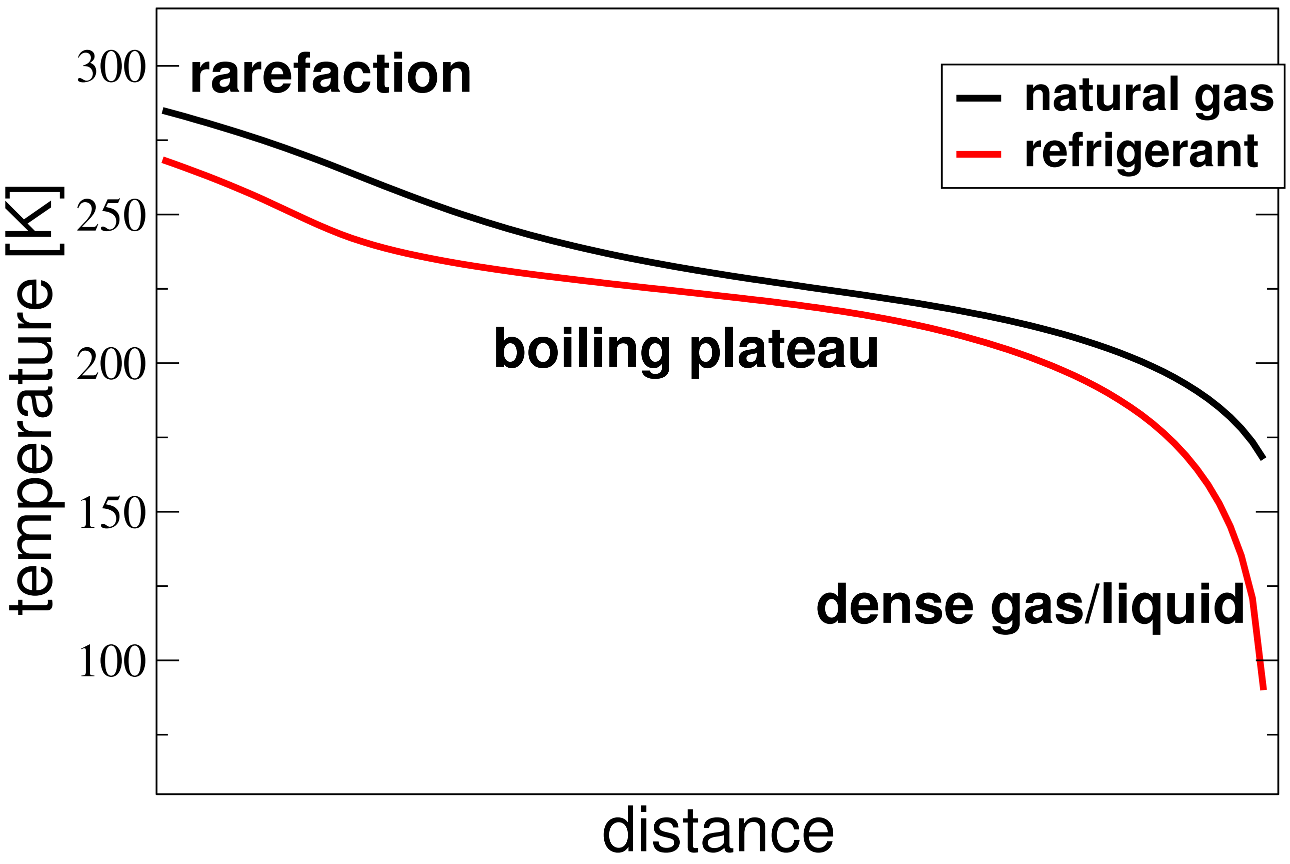
heavy/light fractions MR

heavy/light fractions NG

stable through hot-end up

boiling flow

Generic LNG liquefaction in PFHE



iterative solution

stationary operation

ideal gas mixture

Raoult's law

mainly propane/ethane

matched mass/heat flow

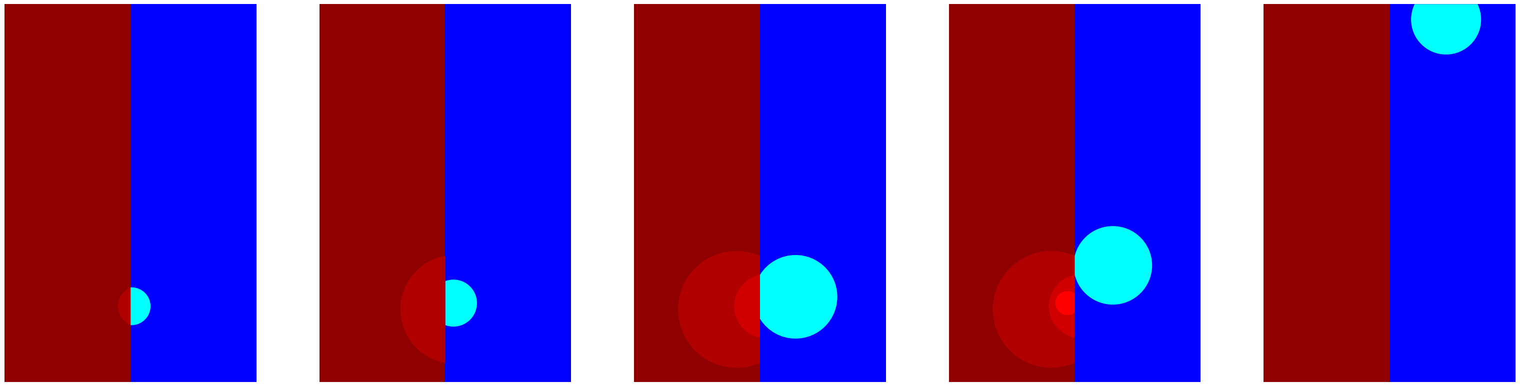
simulation of the heat flows, with fixed composition

Heat transfer: conductivity

- Fluid: limited effects in bulk, boundary effects important
- Wall: complex processes, flow related, boiling
- Aluminum: plate, fin, and axial losses

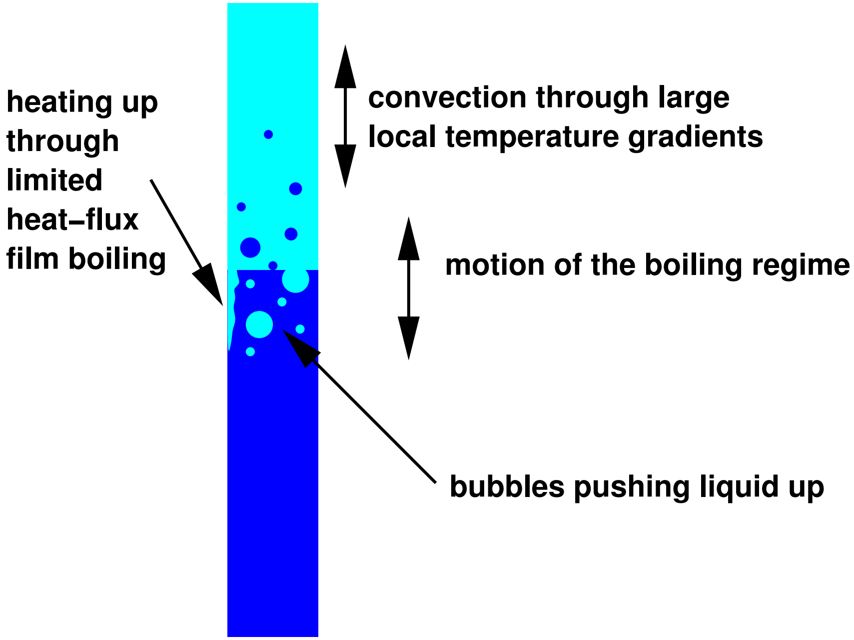
Heat transfer: capacity

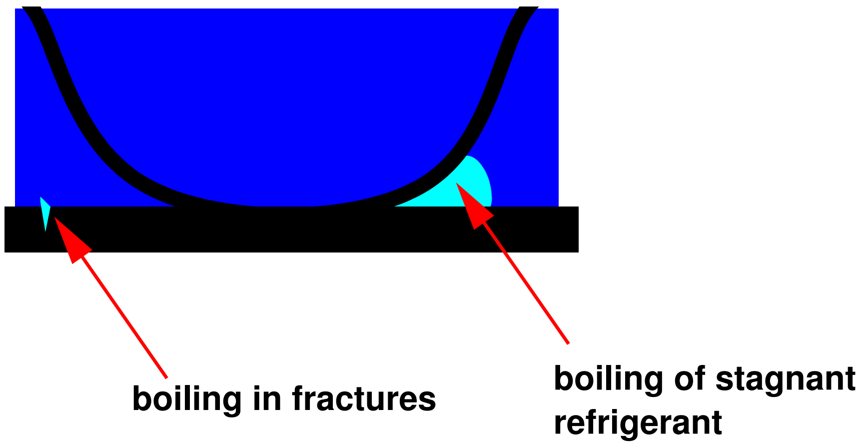
- Fluid: latent heat of boiling, effect of gas density



- nucleating boiling ($\Delta T \sim 10 - 20K$, avoid film boiling)
- low pressure $P < P_c$ for boiling flow (Mostinski rule)
- homogenous flow and fluid temperature (no cracks or corners)

various forms of instabilities in boiling

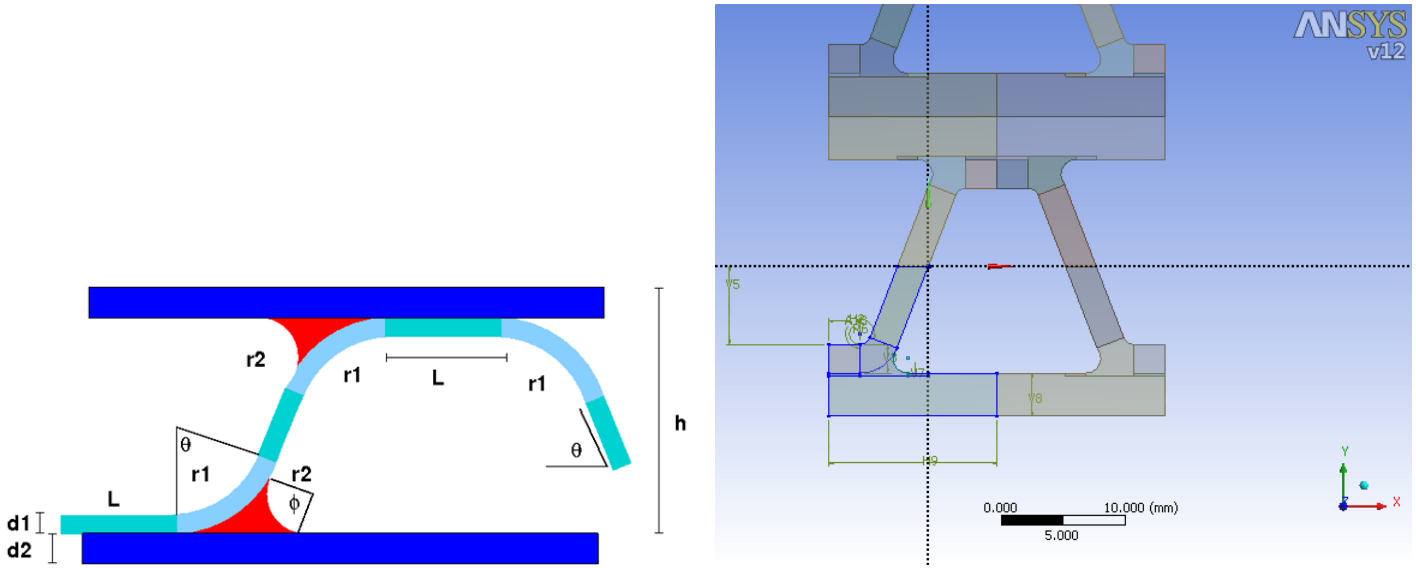




from nucleation, with noise, via cavitation, possible with film flow or convection cells, to bubble and slug flows

Mechanical model, unit cell

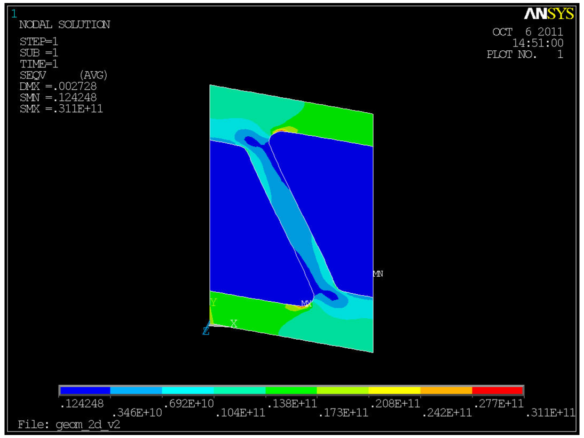
- Brazing material as well as the material of the total structure is aluminum alloy
- There is no prestress at the brazing regions
- Mechanical properties do not depend on temperature

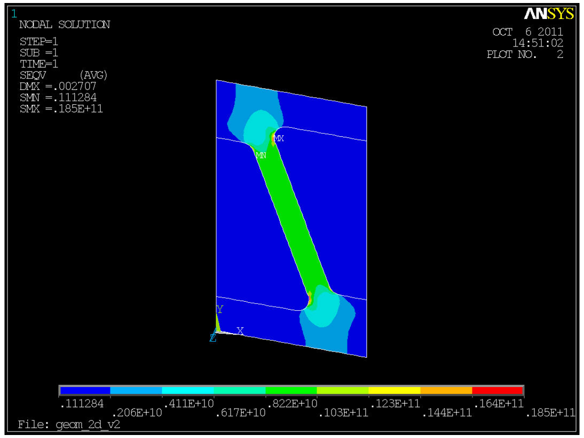


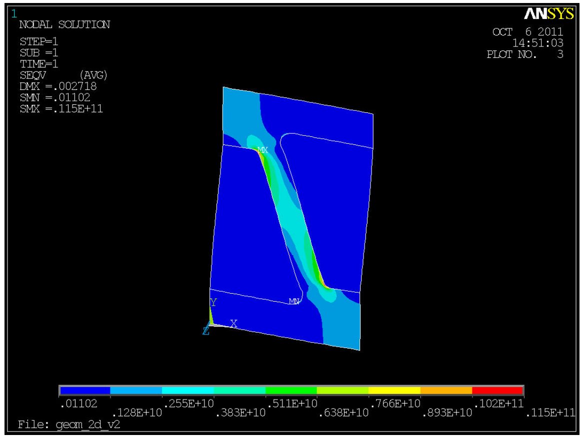
Effective mechanical properties

In order to calculate effective properties of the PFHE,
a series of test problems (uniaxial tension and simple shear) have been solved,

as well as a set of equations from the mechanics of composites





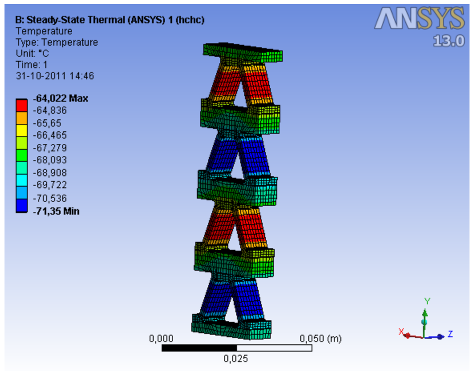


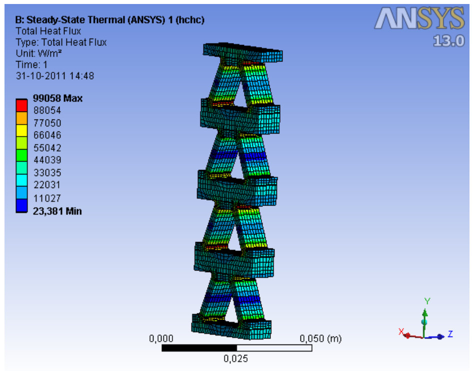
The calculated mechanical properties of the effective orthotropic material are:

$$\begin{array}{lll} E_x = 2.358 \cdot 10^{10}\ \text{Pa} & G_{xy} = 2.29 \cdot 10^{9}\ \text{Pa} & \nu_{xy} = 0.23 \\ E_y = 1.322 \cdot 10^{10}\ \text{Pa} & G_{yz} = 5.68 \cdot 10^{9}\ \text{Pa} & \nu_{yz} = 0.13 \\ E_z = 3.263 \cdot 10^{10}\ \text{Pa} & G_{zx} = 9.63 \cdot 10^{9}\ \text{Pa} & \nu_{zx} = 0.33 \end{array} \qquad (1)$$

Temperature and heat flux profiles in solid part

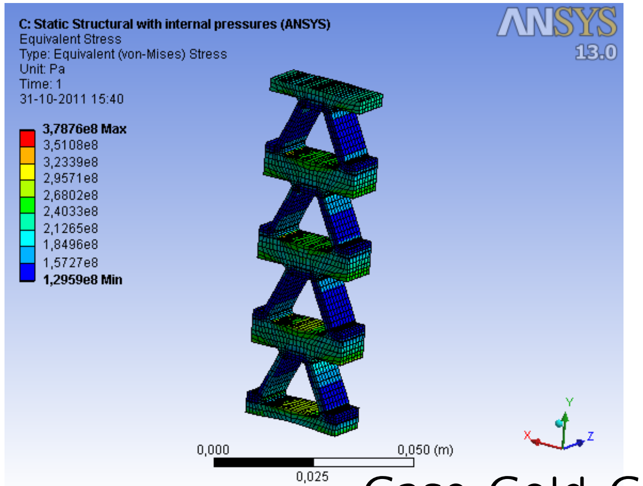
$$\begin{array}{lllll} \text{case 1: Hot-Cold-Hot-Cold} & (T_{hot} = -53C, & h_{hot} = 1000W/m^2C, & P_{hot} = 50bar) \\ \text{case 2: Cold-Cold-Hot-Hot} & (T_{cold} = -73C, & h_{cold} = 4000W/m^2C, & P_{cold} = 5bar) \end{array} \quad (2)$$

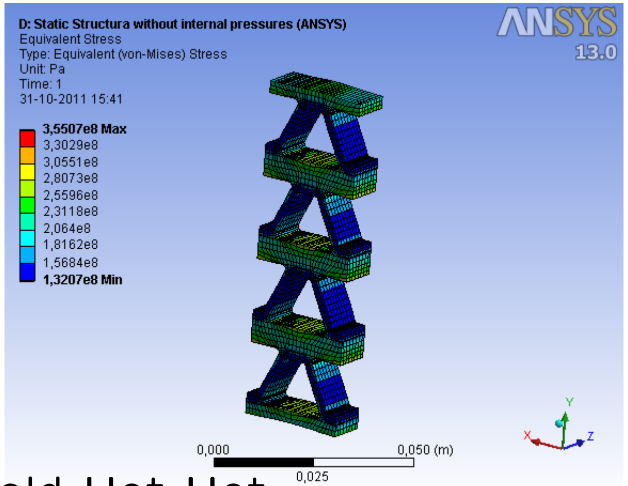




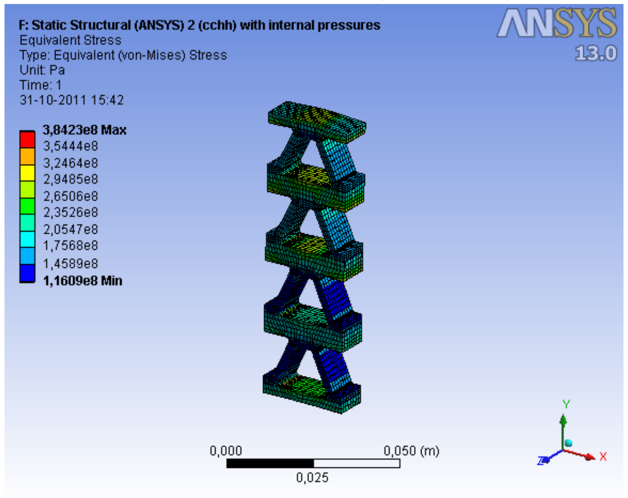
Local stresses with and without internal pressures

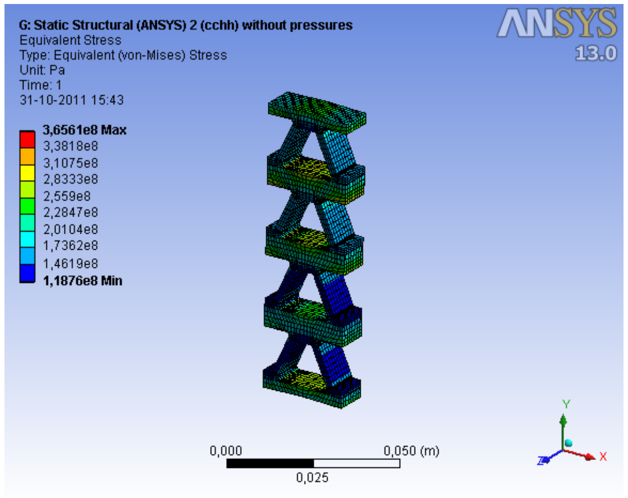
Case Hot-Cold-Hot-Cold



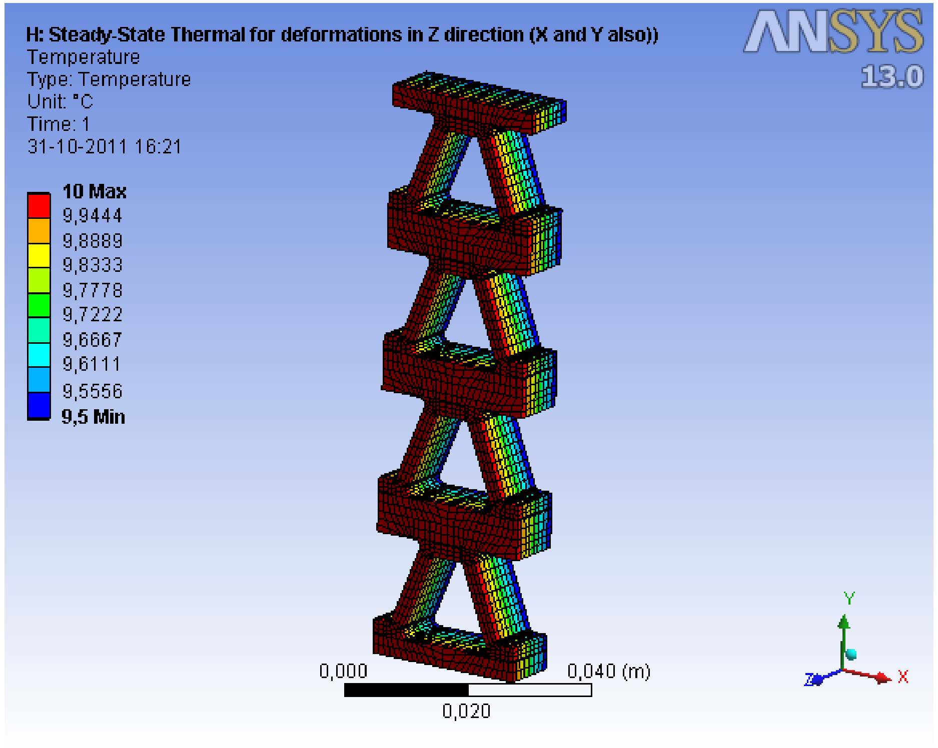


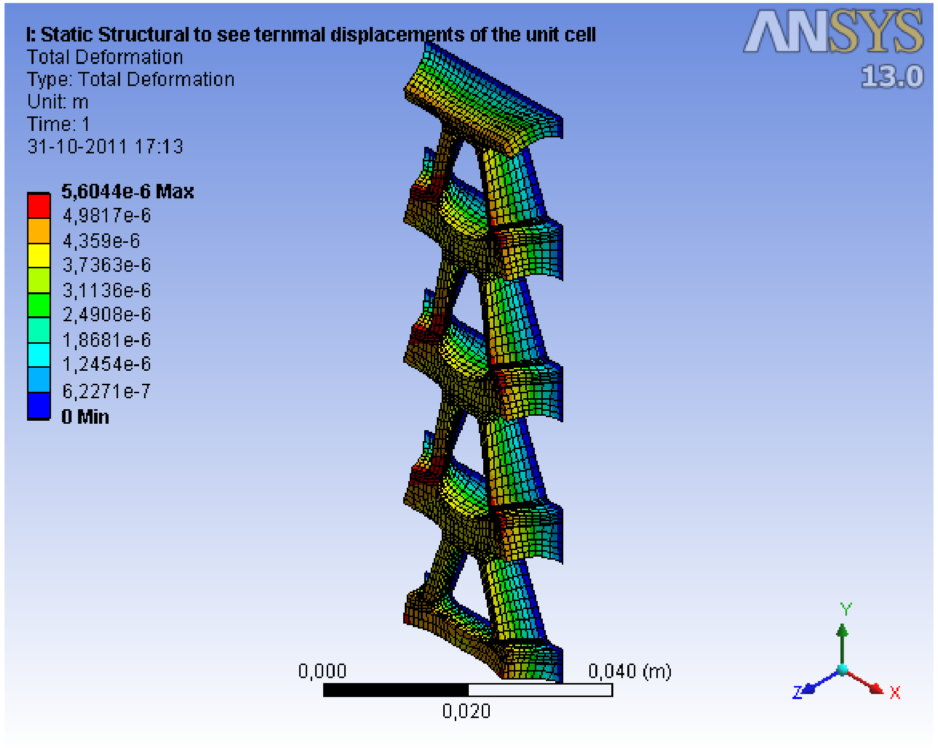
Case Cold-Cold-Hot-Hot



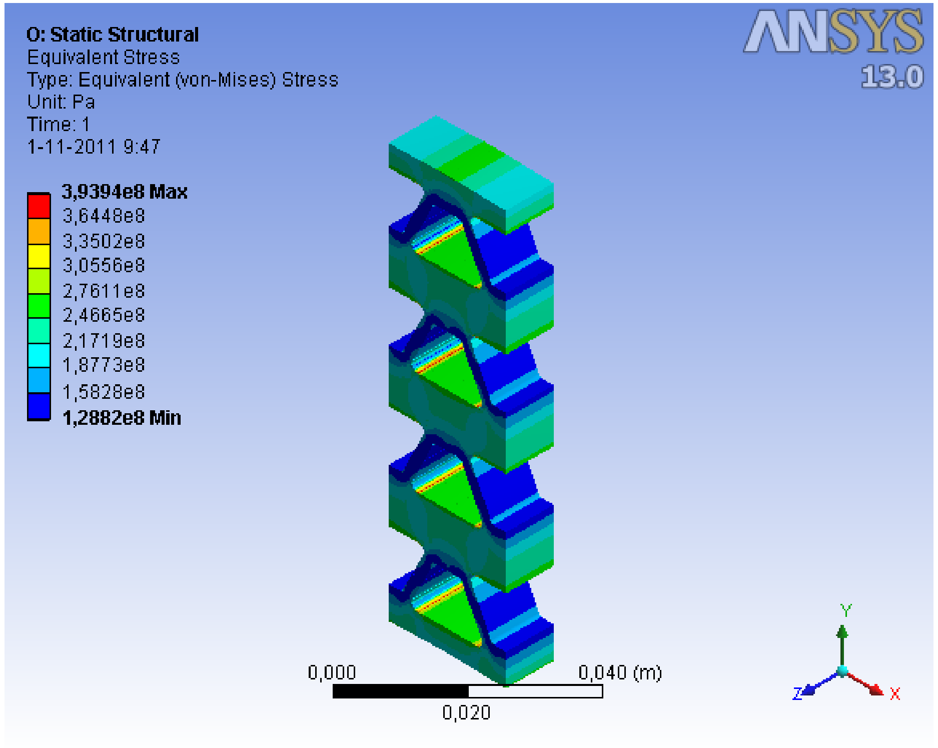


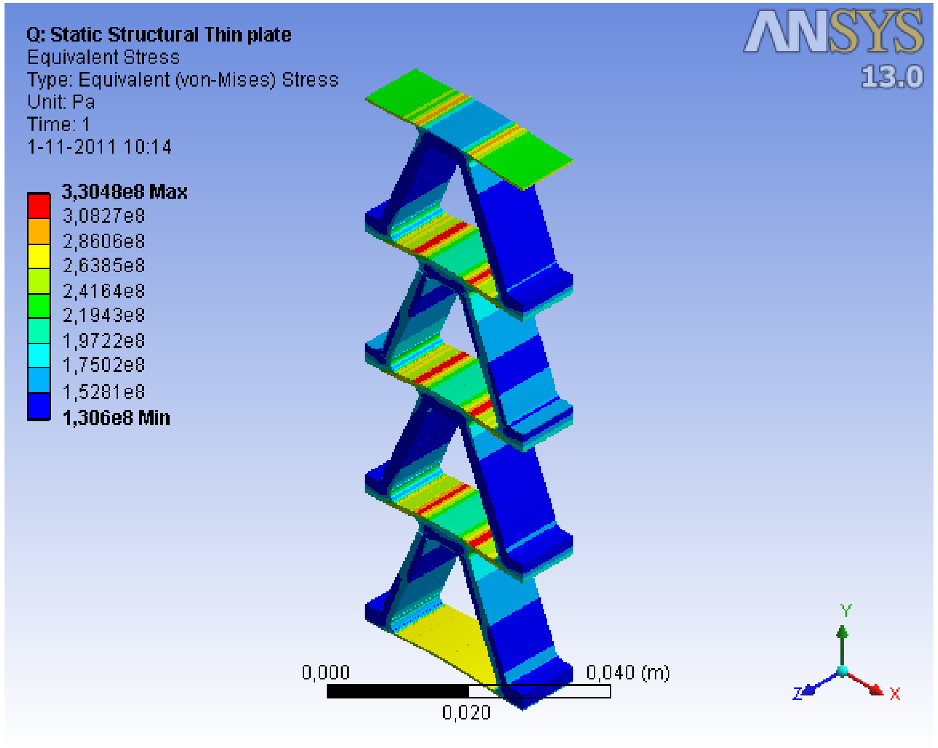
Calculation of global deformations





Stress dependencies on design parameters





design and operational margins

- use small channels: higher pressure, but more area, more stable
- avoid sharp corners in design: no local film boiling
- mean temperature gradient smaller than maximum gradients
- hot-end up: stable shutdown
- lower mass flow or increase pressure to avoid film boiling
- mixed refrigerant (i.e. less volatile components) soften boiling

Conclusions

- Complete simulation of LNG liquefaction process
- Temperature profile and stationary operational conditions for the PFHE have been derived.
- Stationary thermal stresses substantial (for constant operation)
- Effective mechanical properties have been calculated
- Geometry of the PFHE can be now optimized to avoid stress concentrations in the brazing region

Outlook and invitation

- Boiling oscillations yield thermal variations and cyclic stresses
- Fatigue due to cyclic stresses likely with current stress levels and locations
- Variation in design and operation can be treated with the current model, including prestress and manufacturing imperfections
- Looking for industrial partners in validation and optimization phase of the research

temperature profiles indicating different conditions