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
simulation of the heat flows, with fixed composition

iterative solution
stationary operation
ideal gas mixture
Raoult’s law
mainly propane/ethane
matched mass/heat flow
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

- heating up through limited heat-flux film boiling
- convection through large local temperature gradients
- motion of the boiling regime
- bubbles pushing liquid up
- boiling in fractures
- boiling of stagnant refrigerant

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:

\[
\begin{align*}
E_x &= 2.358 \cdot 10^{10} \text{ Pa} & G_{xy} &= 2.29 \cdot 10^9 \text{ Pa} & \nu_{xy} &= 0.23 \\
E_y &= 1.322 \cdot 10^{10} \text{ Pa} & G_{yz} &= 5.68 \cdot 10^9 \text{ Pa} & \nu_{yz} &= 0.13 \\
E_z &= 3.263 \cdot 10^{10} \text{ Pa} & G_{zx} &= 9.63 \cdot 10^9 \text{ Pa} & \nu_{zx} &= 0.33
\end{align*}
\]
Temperature and heat flux profiles in solid part

case 1: Hot-Cold-Hot-Cold
\[ T_{hot} = -53 \, ^\circ C, \quad h_{hot} = 1000 \, W/m^2 \cdot ^\circ C, \quad P_{hot} = 50 \, \text{bar} \]

case 2: Cold-Cold-Hot-Hot
\[ T_{cold} = -73 \, ^\circ C, \quad h_{cold} = 4000 \, W/m^2 \cdot ^\circ C, \quad P_{cold} = 5 \, \text{bar} \]  (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

- **NG**
- **TR**
- **DT**

**ideal process**

**high NG flow**

**high refrigerant flow**

**rarefaction**
(decreased heat flux)

**refrigerant boiling**

**film boiling**