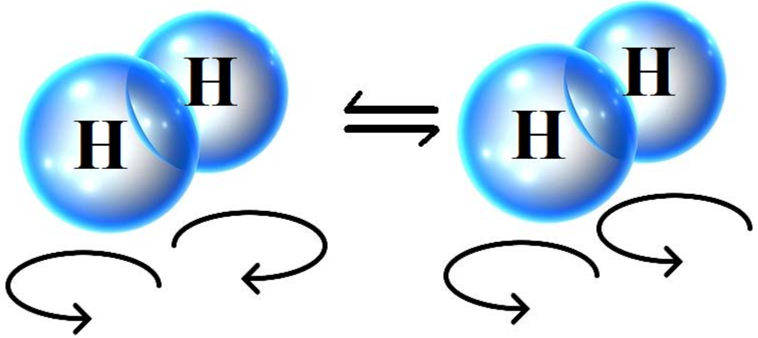

Importance of the heat exchangers in large-scale hydrogen liquefaction

Geir Skaugen and Øivind Wilhelmsen

The Role of Large-Scale Hydrogen, Hyper closing seminar

Brussels, 11-12 December 2019

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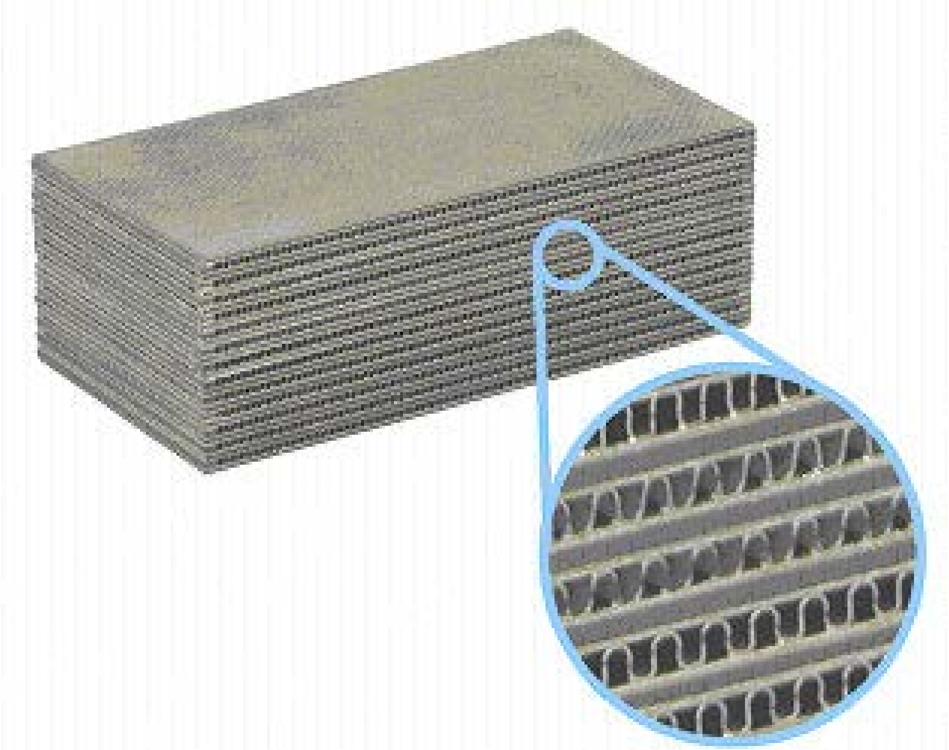
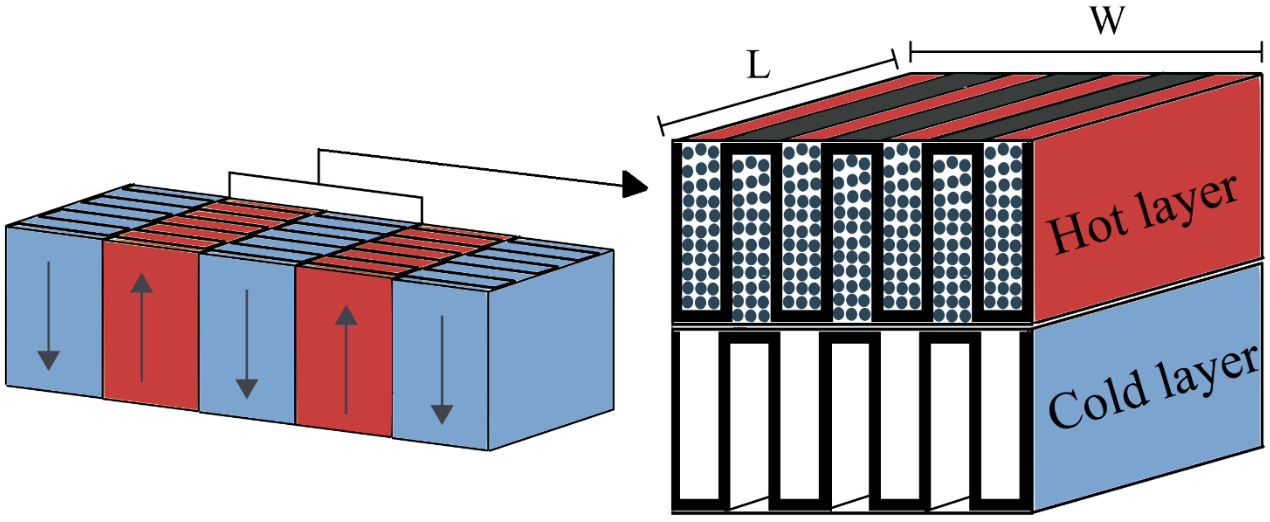
Overview of the presentation

- Overall presentation of modelling of plate-fin and spiral-wound heat exchangers
- A comparison of the two heat exchanger technologies
- Further routes for improvement
    - Improved catalyst for ortho-para conversion
    - The use of novel quantum refrigerants
- A summary

State-of-the-art plate-fin heat exchanger model



© Lytron Inc.: a plate-fin heat exchanger for aircraft cabin environmental control systems



A mathematical model was constructed by solving energy, mass and momentum balance for each layer - using local, spatial wall temperatures

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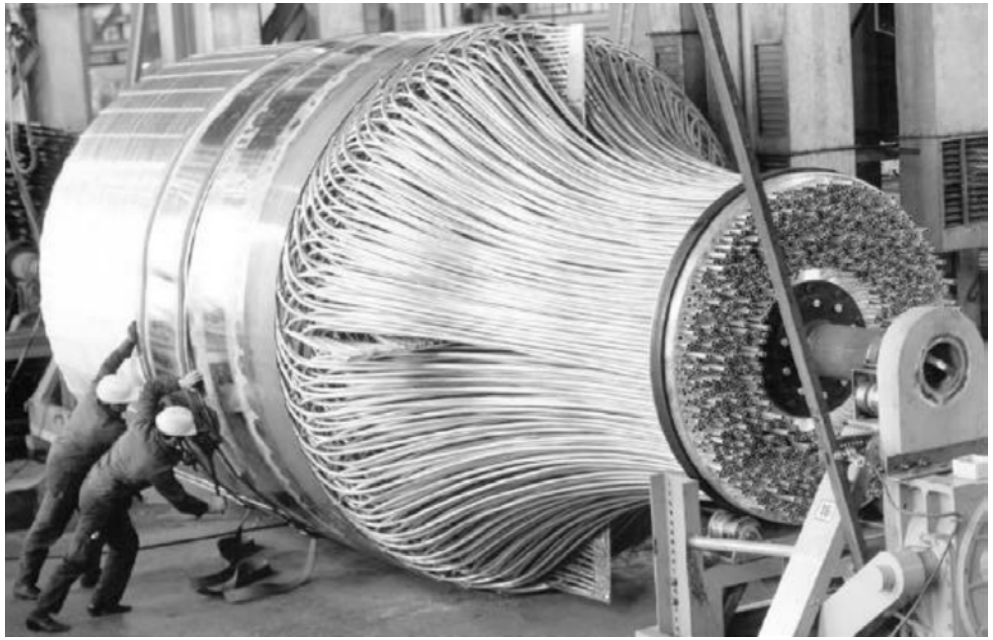
State-of-the-art spiral wound heat exchanger model

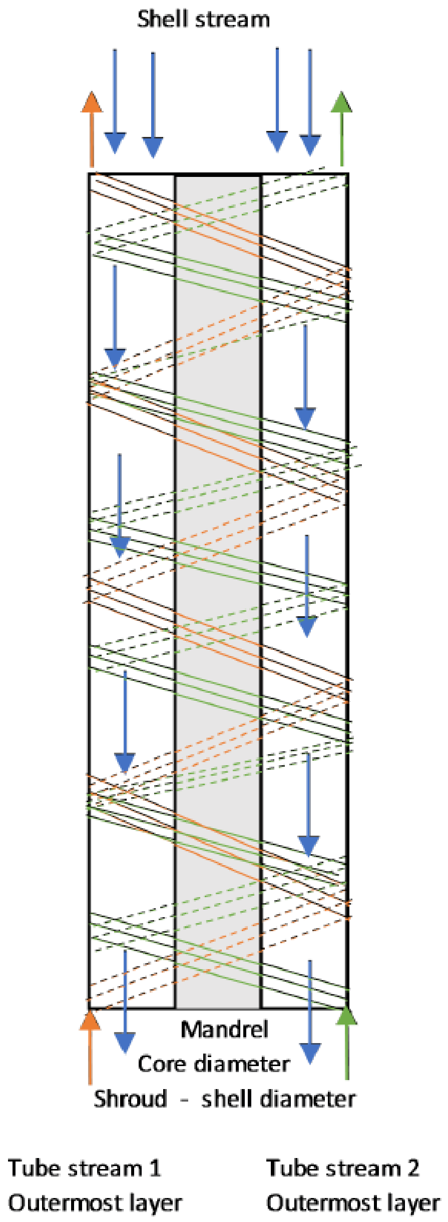


© Linde A.G: a spiral wound heat exchanger for Liquefaction of natural gas

The warm streams flow inside the wounded pipes, counter currently with the cold stream that flows on the shell side.

Different helix angle of the hot streams can be chosen to have different thermal lengths.

It is necessary to fill the pipes where the production hydrogen flows with catalyst.



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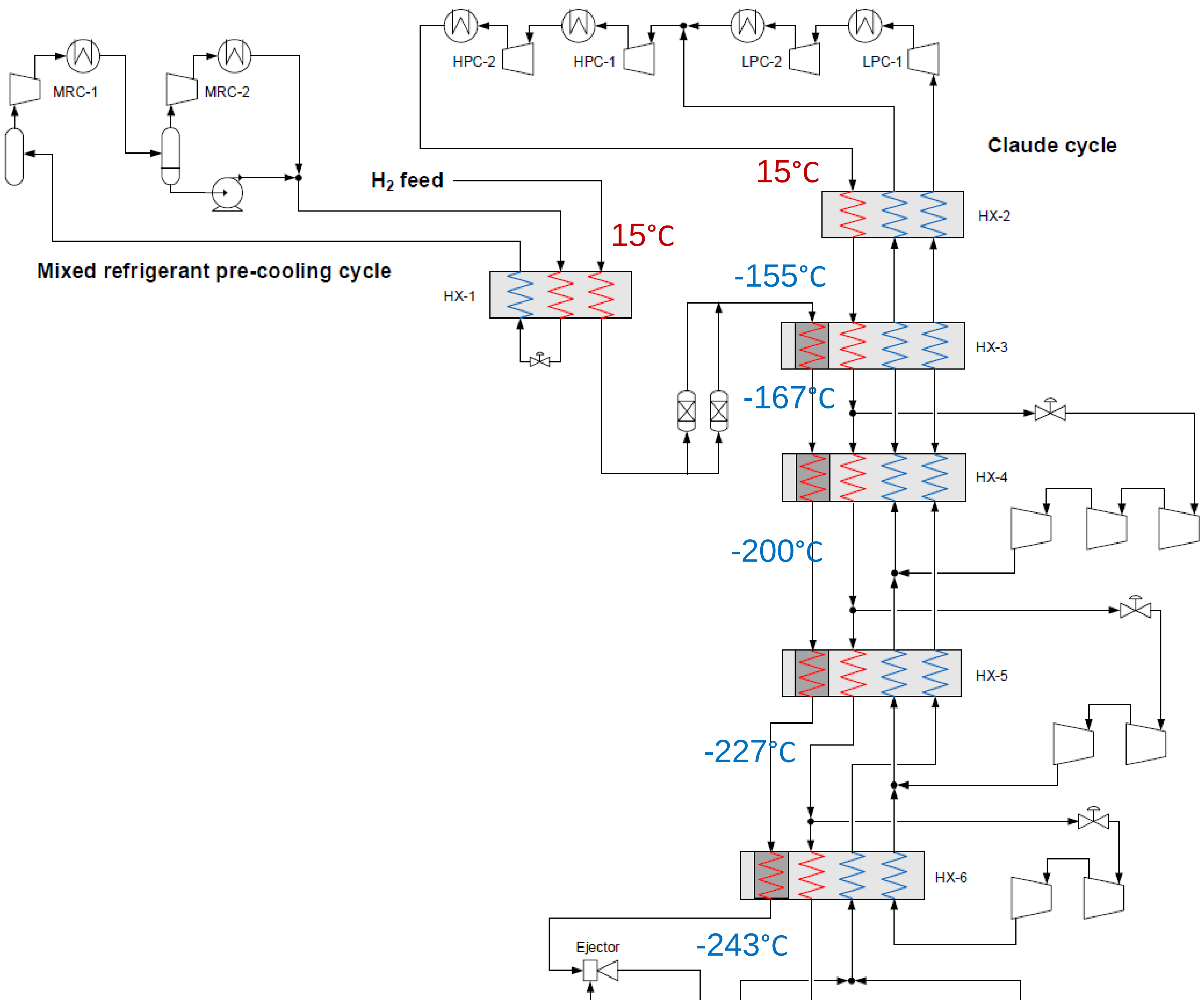

The main heat exchanger of a large-scale (125 tons/day) hydrogen Claude refrigeration process is shown to the left.

The streams are:

- H_2 Feed
- High pressure MR
- Low pressure MR
- Low pressure H_2 refr.
- Medium pressure H_2 refr.
- High pressure H_2 refr.

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The local exergy destruction

$$\dot{E}_{\mathrm{d}} = \dot{E}_T + \dot{E}_P + \dot{E}_{Rx} =$$

$$\int_0^L \left[\underbrace{\sum_{i=1}^{n} \sum_{k=1}^{n} \frac{T_0 \gamma_{i,k} J_{q,k,i}}{2} \left(\frac{1}{T_i} - \frac{1}{T_k} \right)}_{\dot{e}_T} \right] dz +$$

$$\int_0^L \left[\underbrace{\sum_{i=1}^{n} T_0 A_i v_i \left(-\frac{1}{T_i} \frac{dp_i}{dz} \right)}_{\dot{e}_P} \right] dz +$$

$$\int_0^L \left[\underbrace{\sum_{i=1}^{n} T_0 A_i r_{o \to p} \left(-\frac{\Delta G_{o \to p,i}}{T_i} \right)}_{\dot{e}_{Rx}} \right] dz,$$

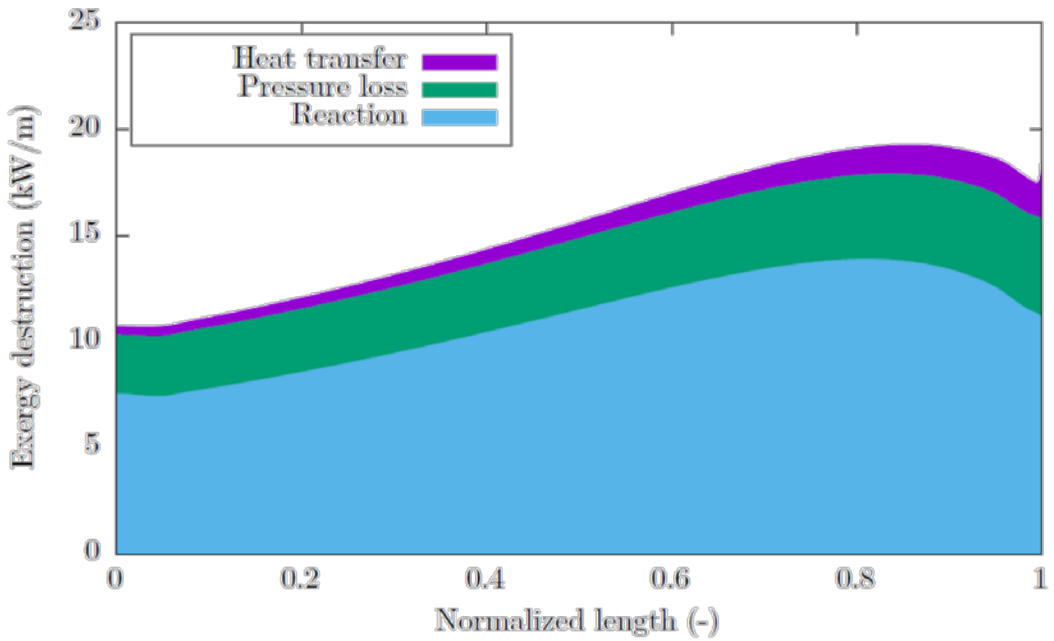
- Local and total exergy destruction in the heat exchangers from 3 different phenomena

A) Heat transfer

B) Pressure drop

C) Spin-isomer reaction

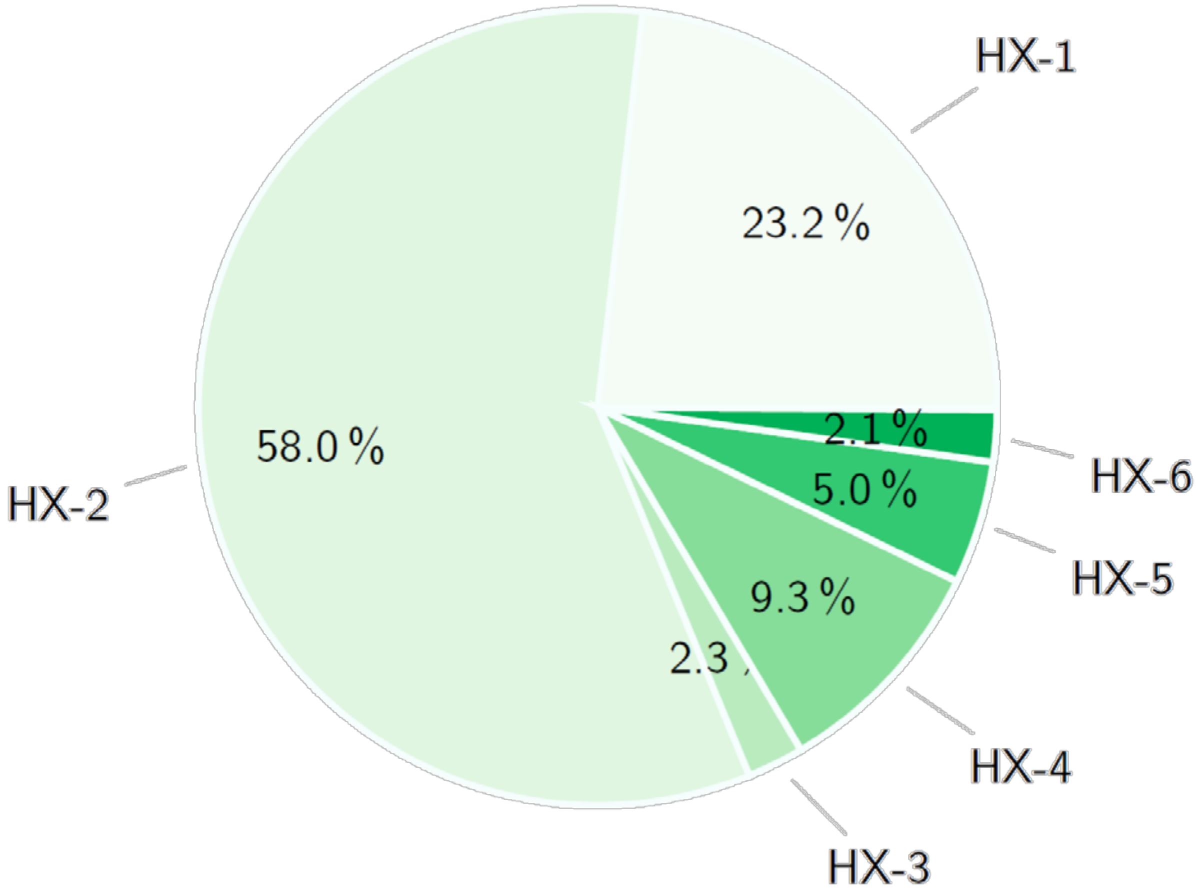
Example from feed stream in HX-4 (PFHE)



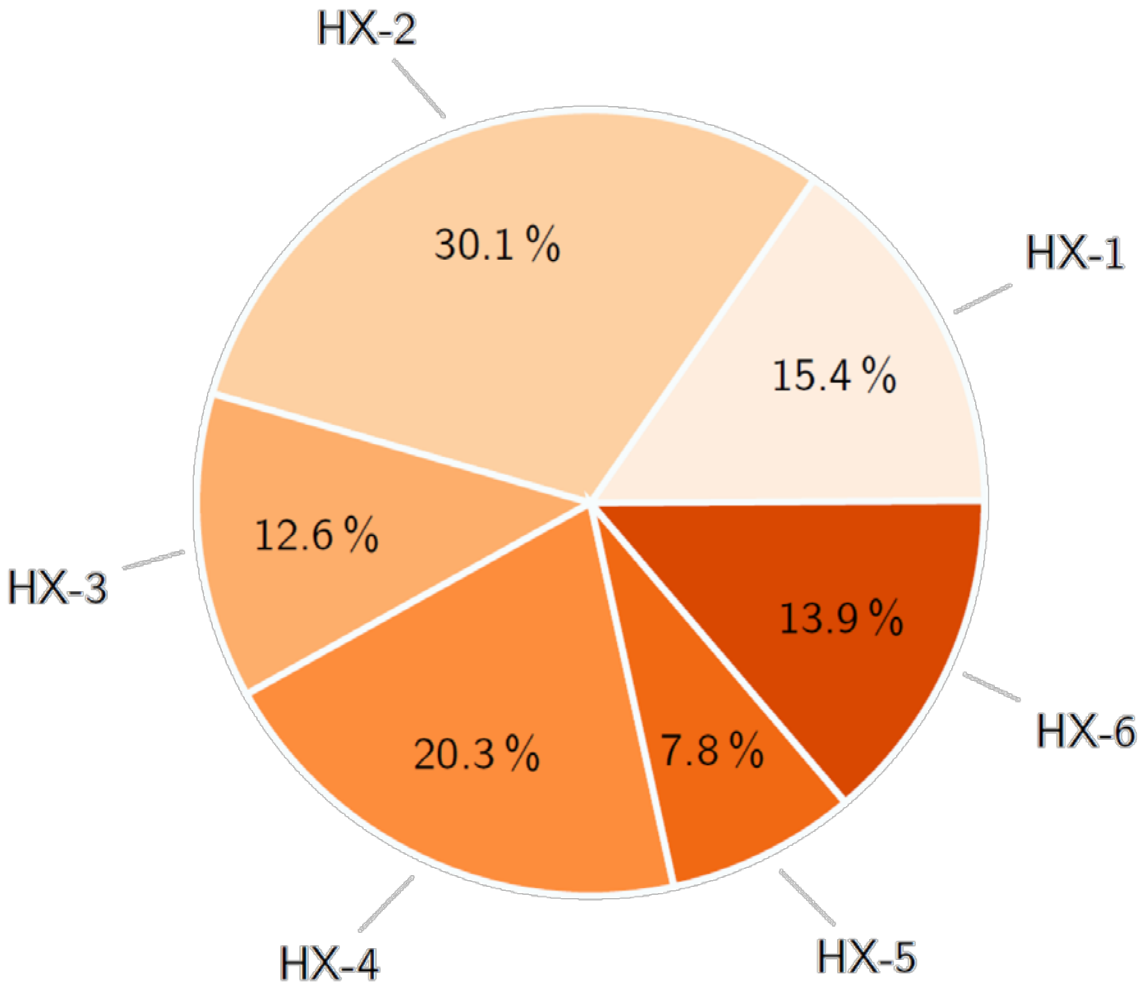
COLD

WARM

Duty vs exergy destruction within the plate-fin heat exchangers



Duty



Exergy destruction

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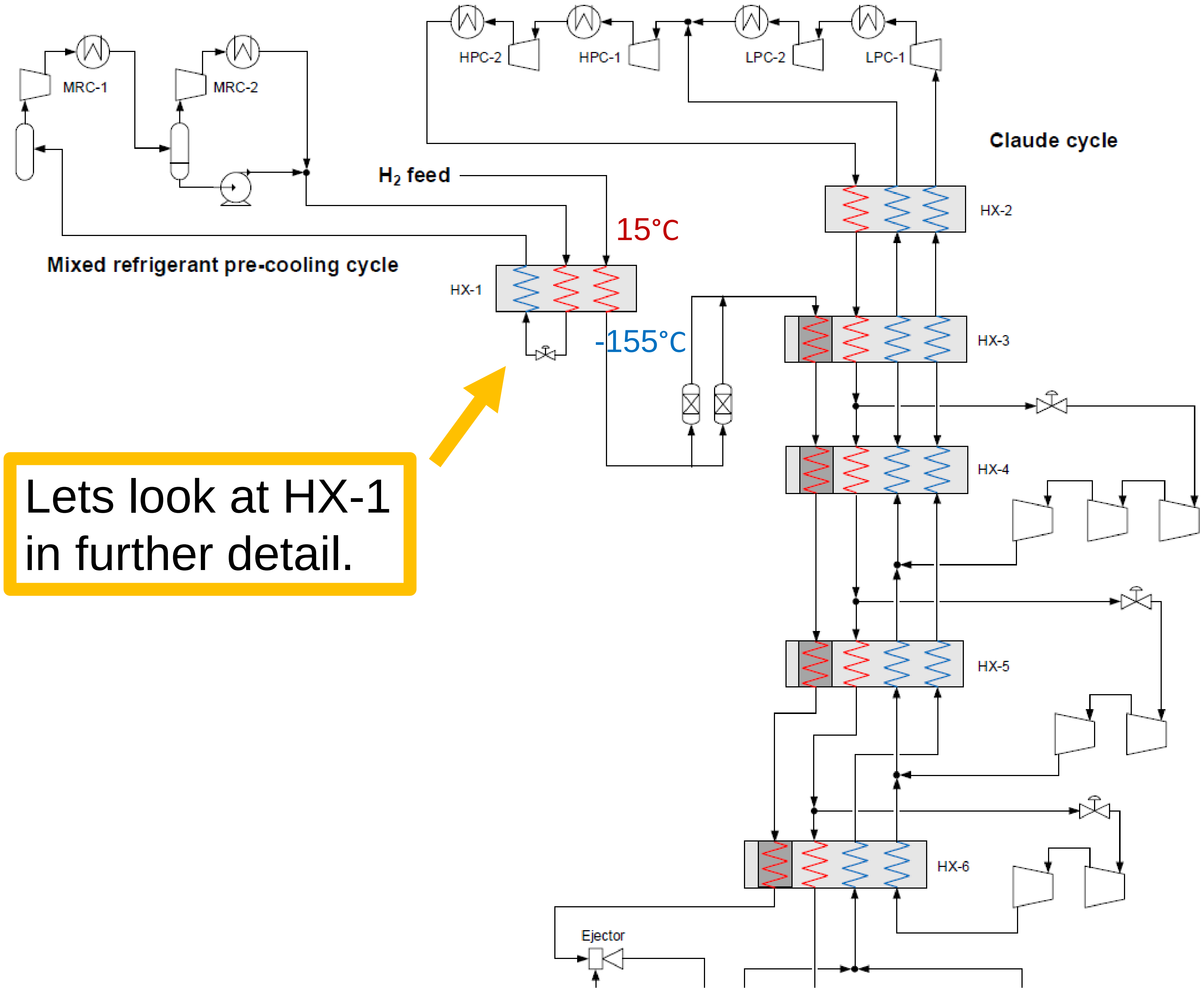


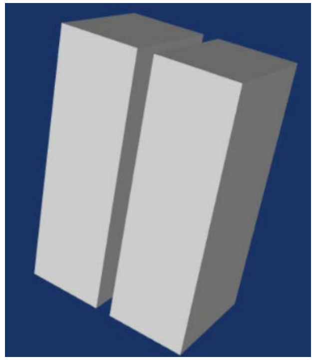
Lets look at HX-1 in further detail.

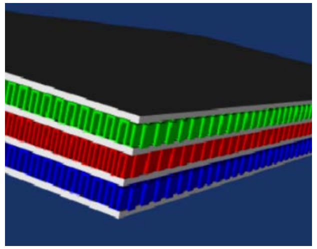
The main heat exchanger of a large-scale (125 tons/day) hydrogen Claude refrigeration process is shown to the left. The streams are:

- H_2 Feed
- High pressure MR
- Low pressure MR
- Low pressure H_2 ref.
- Medium pressure H_2 ref.
- High pressure H_2 ref.

Design of HX-1
(Duty 12.7 MW)

Plate-fin





Length: 3.51 m

Height: 2.19 m

Parallel modules: 2

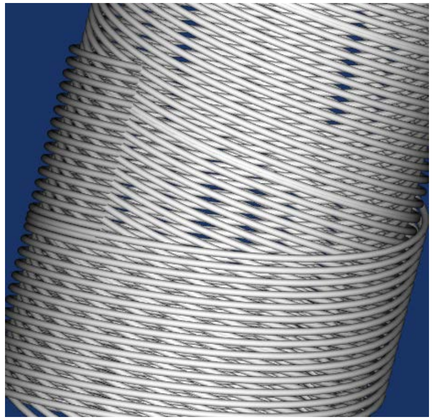
Layers: 330

Weight: 14.6 ton

Surface density: 1253 m^2/m^3

Exergy destruction: 761 kW

Spiral-wound



Length: 15 m

Diameter: 4.66 m

Parallel modules: 1

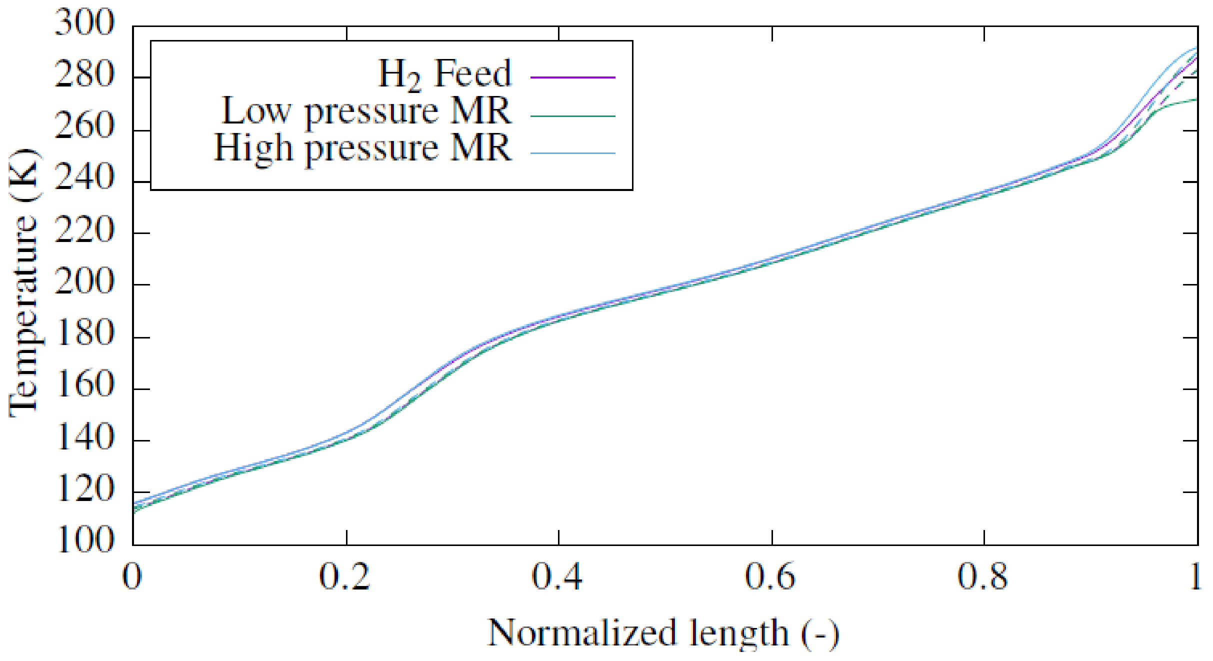
Layers: 120

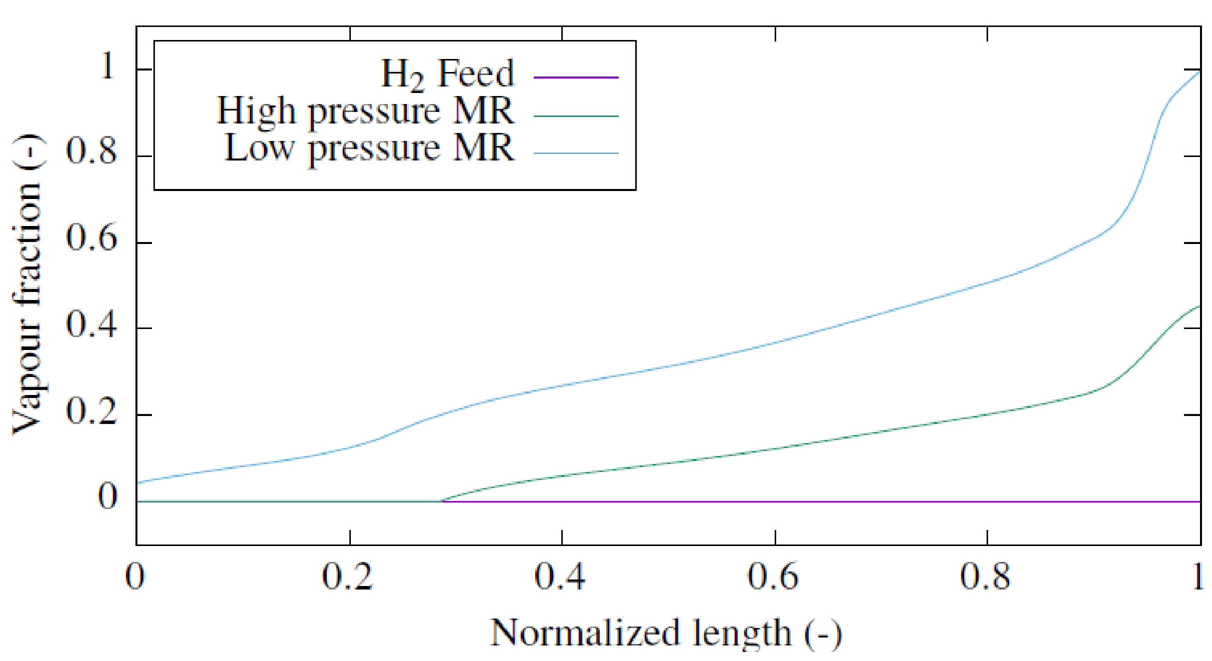
Weight: 172.32 ton

Surface density: 271 m^2/m^3

Exergy destruction: 441 kW

Temperature and vapor-fraction through PFHE





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The local exergy destruction in HX-1 (MR precoooler)

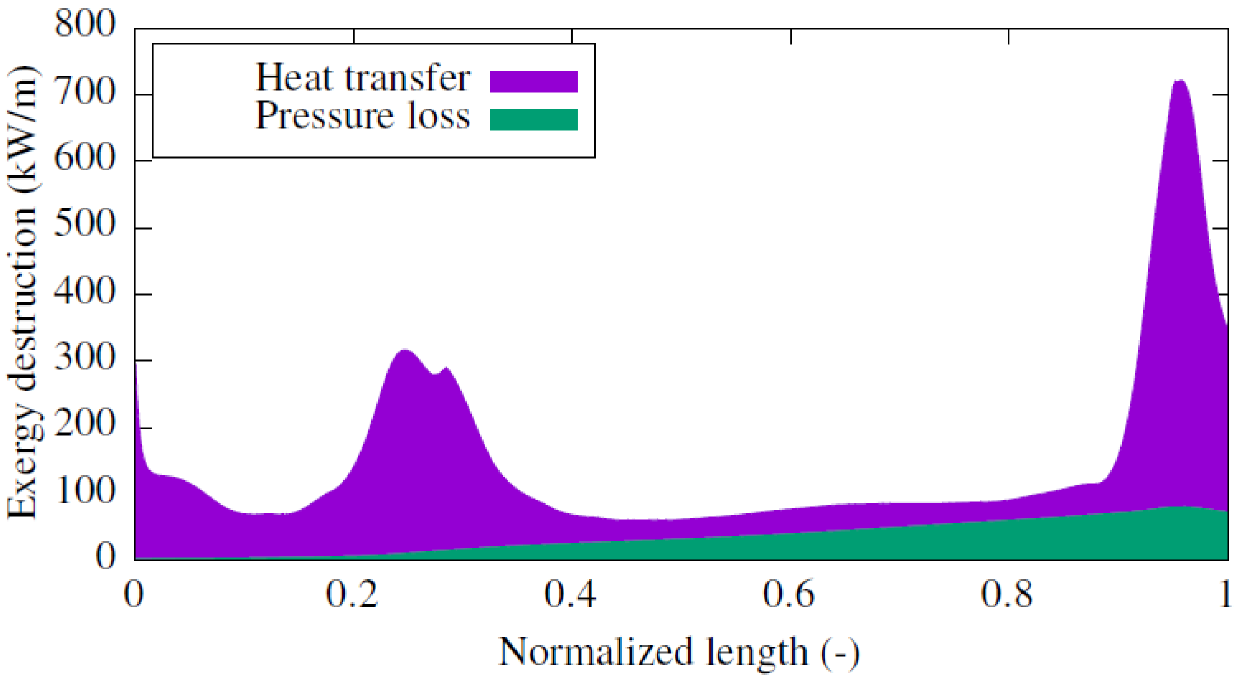
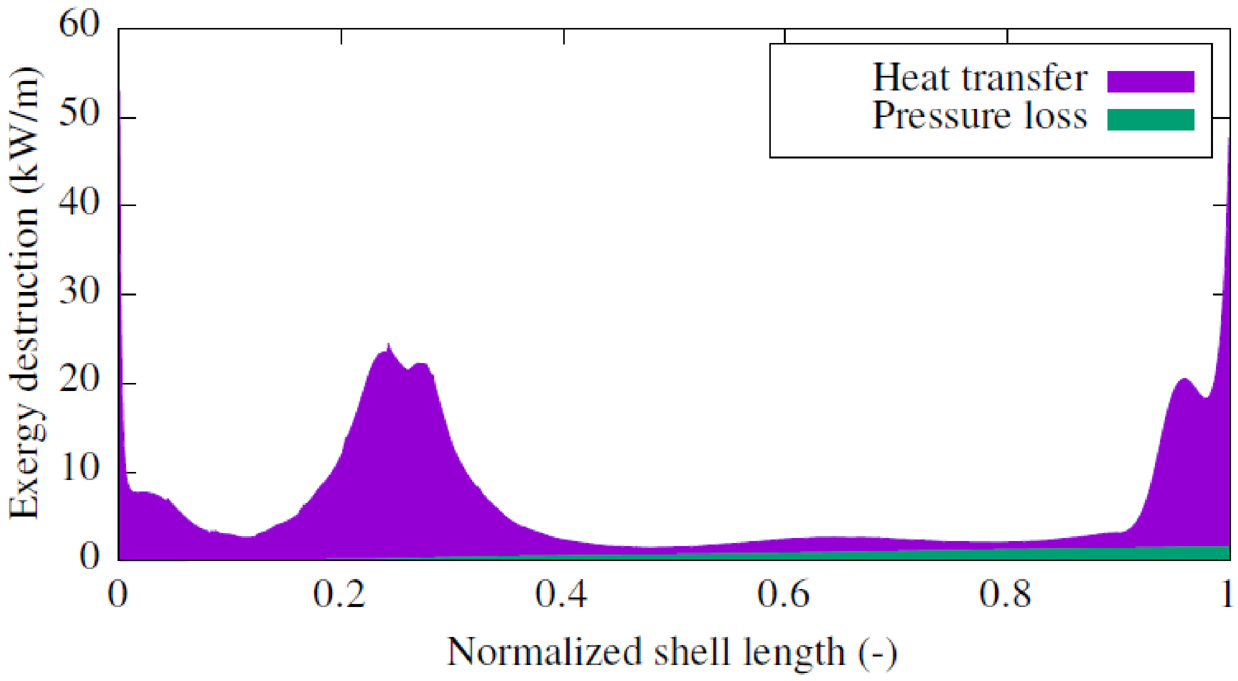


Plate-fin heat exchanger

(Total: 761 kW)



Spiral-wound heat exchanger

(Total: 441 kW)

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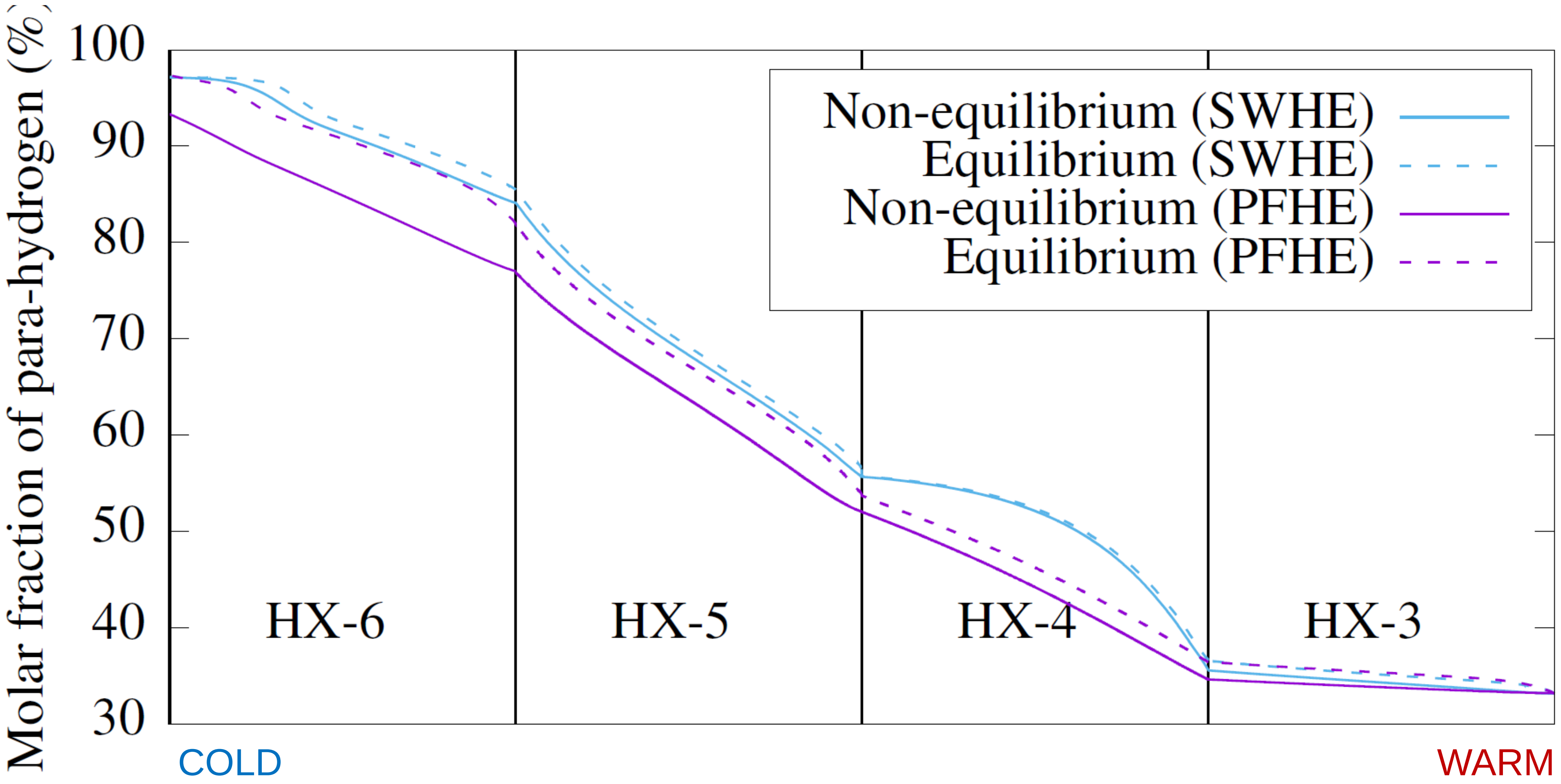
Results from the analyzis

- One should use a dual MR or a cascade process to improve the performance of HX-1
- The local exergy destruction maps also show how to reduce exergy destruction in the rest of them, e.g. by changing layer distribution.
- Due to the much larger size of the spiral-wound heat exchangers, plate-fin heat exchangers are probably the best choice.

The mole fraction of para hydrogen – non equilibrium



Ortho-para hydrogen conversion makes up **6%** of the total exergy destruction in the plate-fin heat exchangers, and **2%** in the spiral wound heat exchanger. Outlet composition of para-hydrogen is not high enough from the last plate-fin heat exchanger - **93%** vs **97%**

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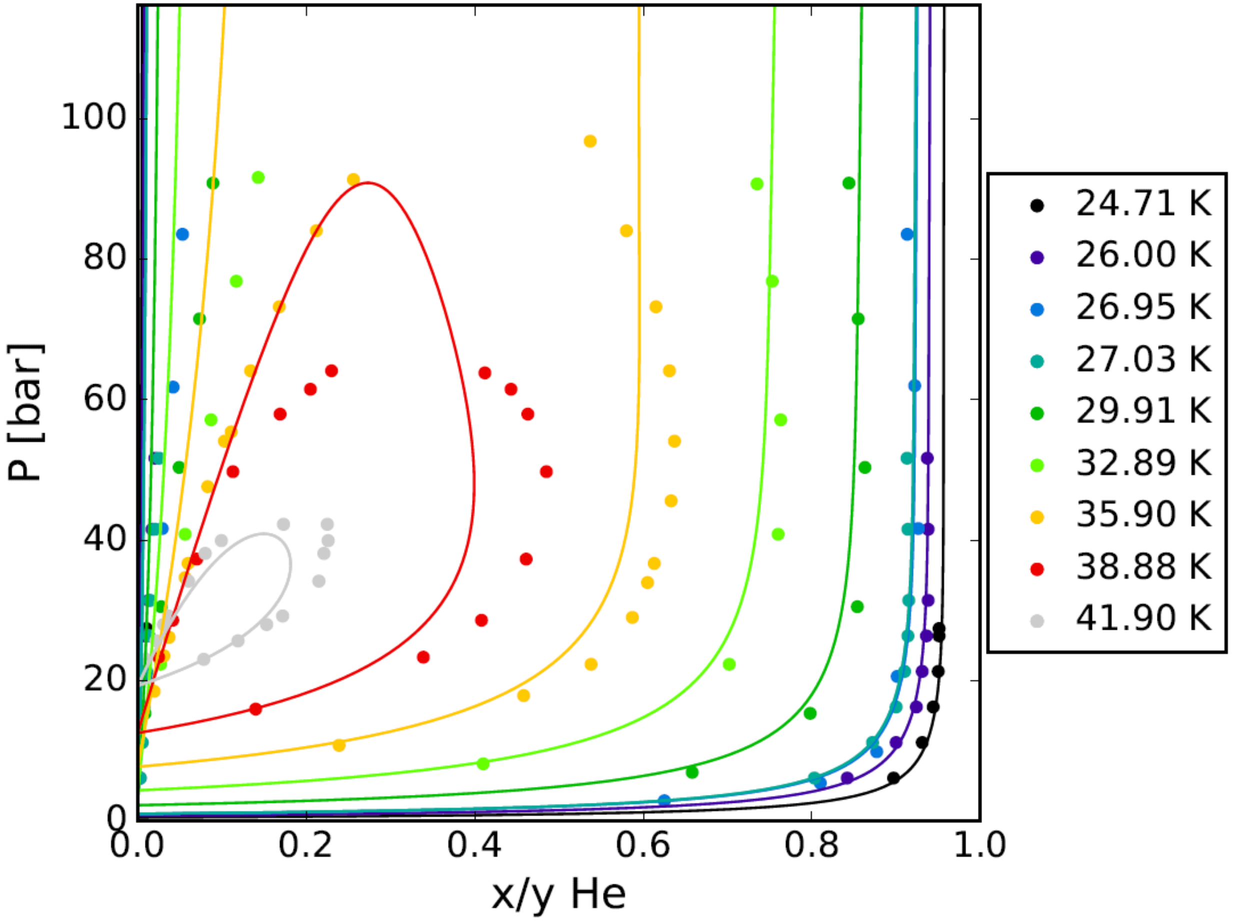
Short summary

- Dual MR circuit can reduce the exergy destruction in HX-1 by more than 60%.
- Design of all HX should be optimized, tradeoff between pressure drop and flow rates.
- In HX-6 the spiral wound heat exchanger can be used to improve the efficiency much due to more favorable ortho-para conversion profile
- In total, we estimate that more than 1000 kW of the losses can be reduced – which represent about 0.20 kWh/kg LH_2.

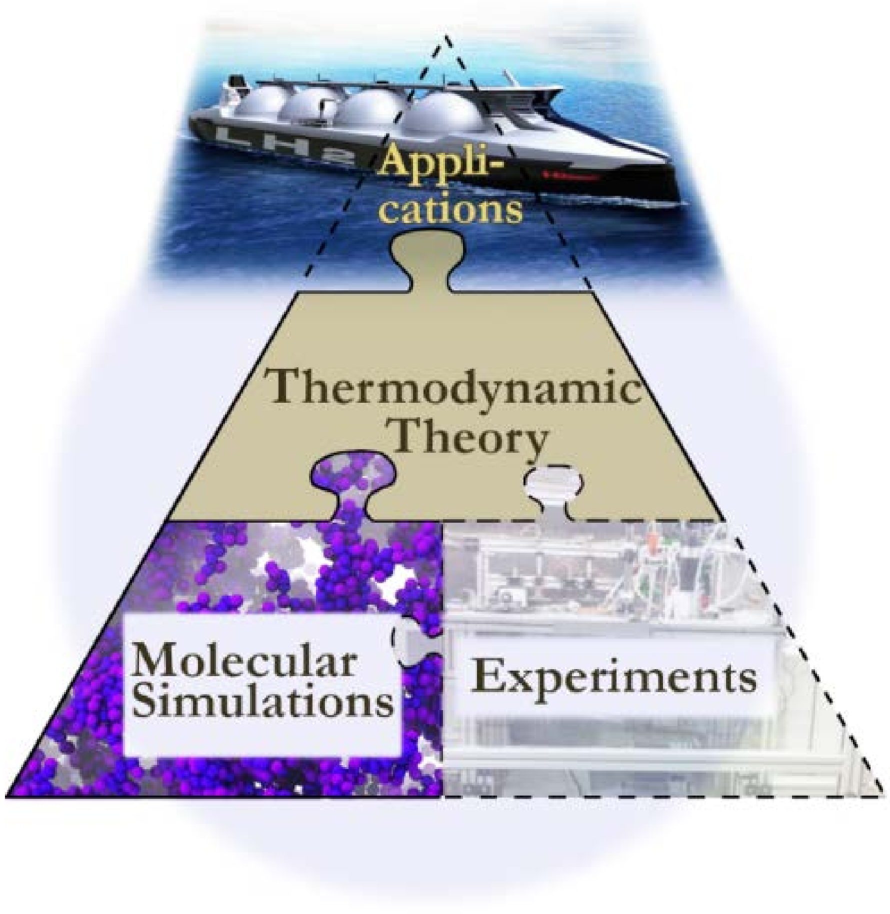
Next step – novel refrigerant H_2-Ne-He



- Present EoS, e.g. cubic EoS with advanced mixing rules of SAFT variant do not work, why?

Quantum effects

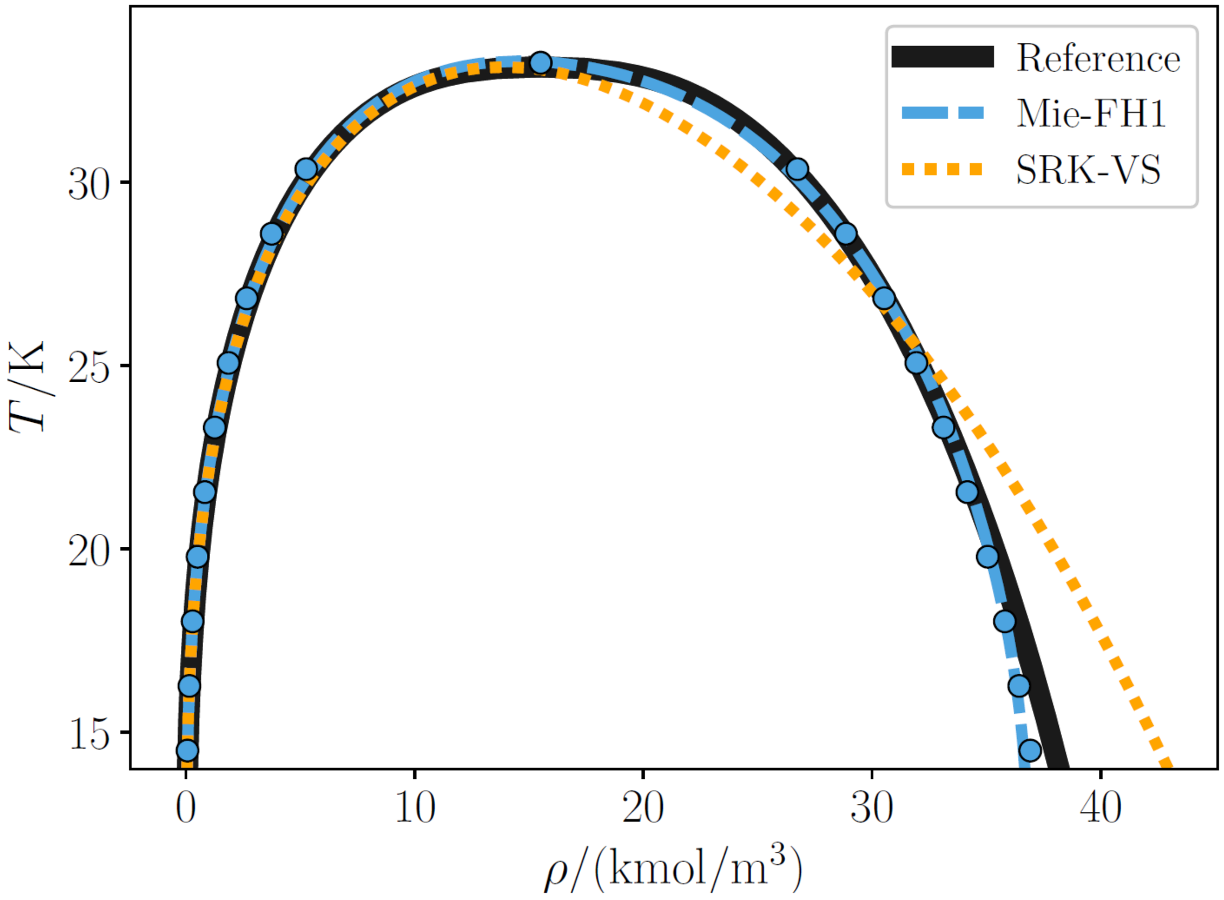
The SINTEF Quantum SAFT Equation of State



We have developed a new equation of state for novel quantum refrigerants

- The EoS represents accurately experimental thermodynamic data for He, De, H_2 and Ne.
- Captures also the thermodymic properties of the interaction potential for use in mol. simulaions

Hydrogen



The figure demonstrates a really good match with experimental data (black solid line) and simulation results (blue dots).

Much better than SRK.

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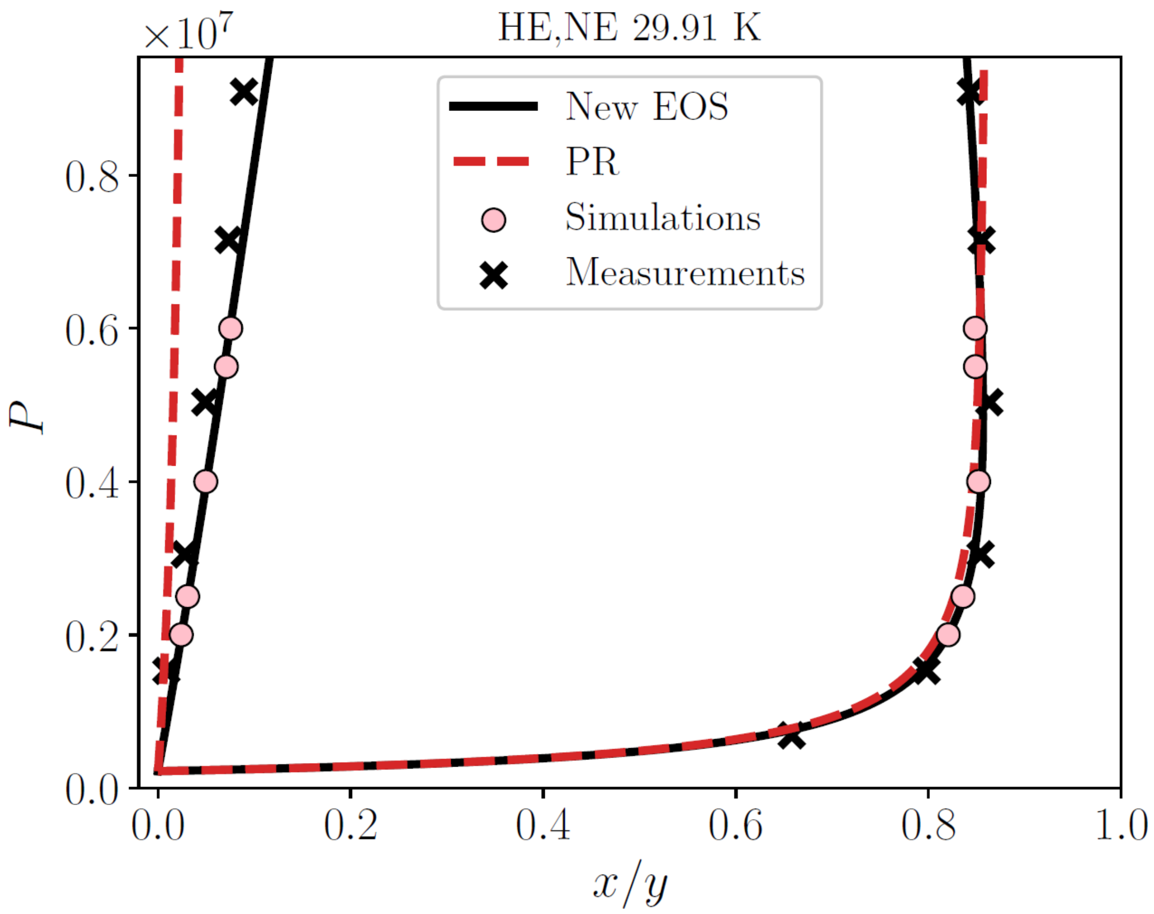
What about mixtures? Helium-Neon is below



Improves the situation much for helium-neon.

Would trust the simulation results even more than experiments here (exps. do not extrapolate to right P_{sat})

All properties are more accurate

Summary

- We have developed a state-of-the-art modelling and design tool for catalyst-filled plate-fin and spiral-wound heat exchangers including conversion of ortho-to-para hydrogen and a detailed exergy destruction map.
- We have also developed a state-of-the-art thermodynamic description of He-Ne-H_2 mixtures and coupled it to heat exchanger design tool and process simulator.
- Large potential for improved LH_2 process with tailormade dual MR precooling section and specially designed He-Ne-H_2 composition for efficient turbocompressor utilization and boiling refrigerant at lowest temperatures. Possible freeze-out of neon must be addressed.

Acknowledgements

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Developing a model for the ortho-para hydrogen conversion rate

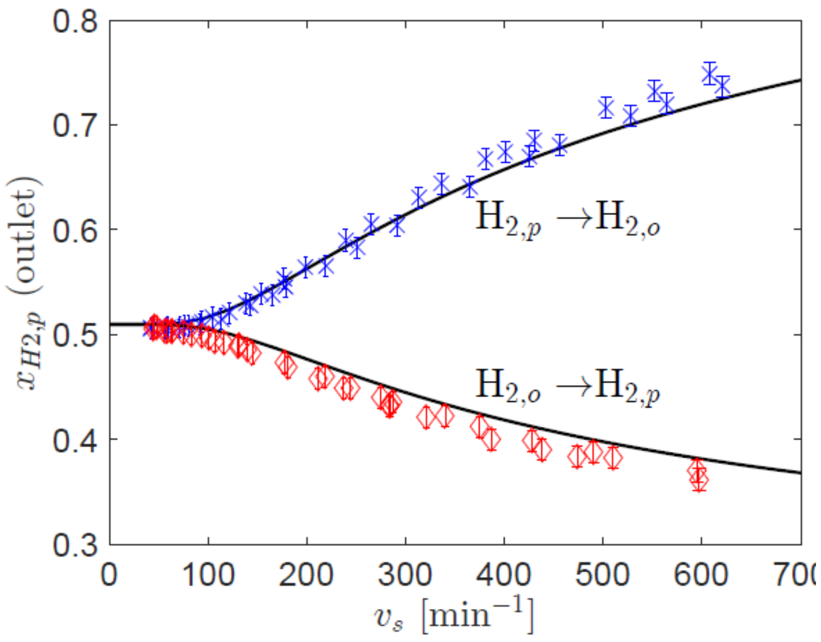
The data by Hutchinson[1] have been used, more experimental data on conversion rate is needed.

$$\frac{\mathrm{d}\dot{m}_{H_2,\mathrm{p}}}{\mathrm{d}z} = A\eta \; r_{\mathrm{o}\rightarrow\mathrm{p}}$$

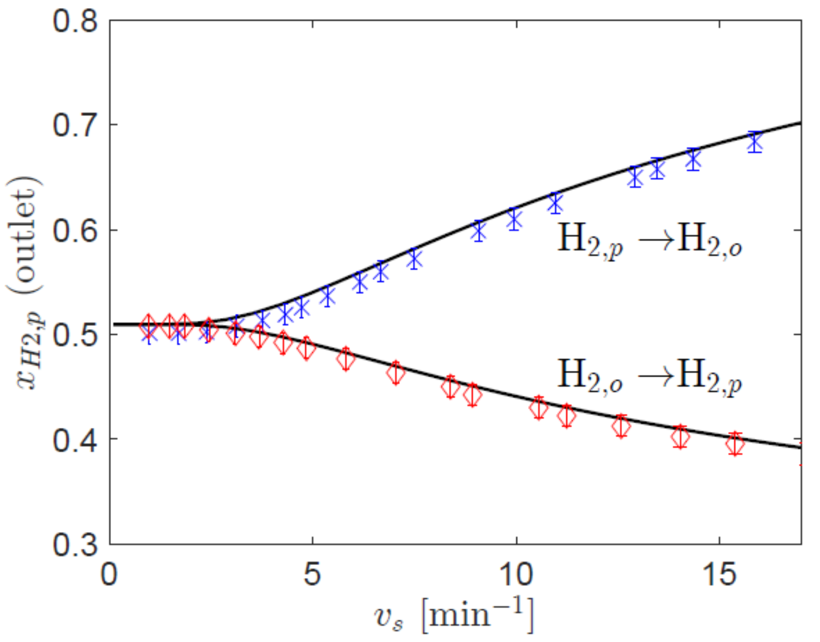
$$r_{o\rightarrow p} = K \ln\left[\left(\frac{x_{H_2,\mathrm{p}}}{x^{\mathrm{eq}}_{H_2,\mathrm{p}}}\right)^n \left(\frac{1 - x^{\mathrm{eq}}_{H_2,\mathrm{p}}}{1 - x_{H_2,\mathrm{p}}}\right)\right]$$

Here, n should be positive and a function of *T*, while K should be a function of both *P* and *T*.

Only four fitting parameters were needed to achieve a very accurate fit.



(a) P = 0.21 MPa



(b) P = 6.96 MPa

[1] Hutchinson, Adv. In Cryog. Eng. 10, 1965.

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