Use of sophisticated heat exchanger simulation models for investigation of possible design and operational pitfalls in LNG processes

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- Tools for the job:
  - Aspen Hysys + SQP routine for optimisation
  - Detailed heat exchanger model
  - HX model in a Pro/II simulation environment
- Results:
  - Optimised solution
  - Validate solution against a heat exchanger design
  - Validate heat exchanger design against process operability
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Introduction – process optimisation

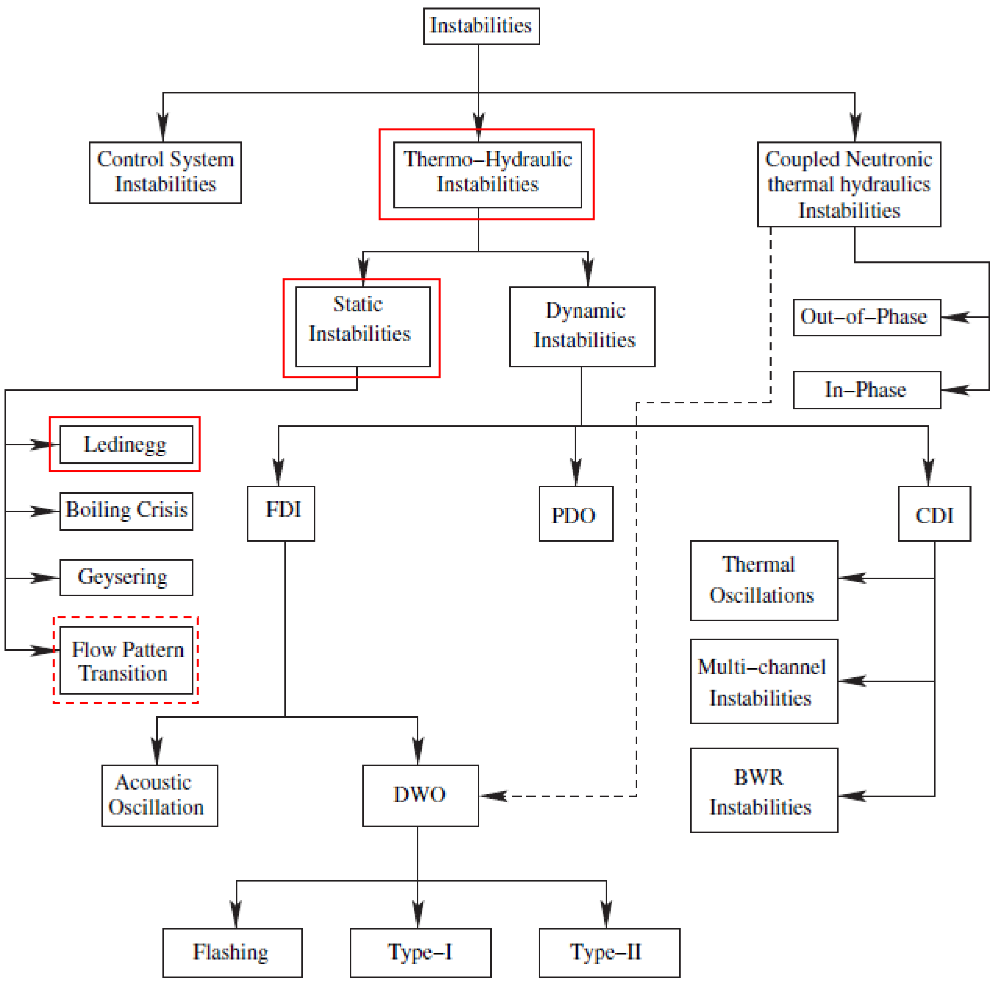
- Objective: Cooling and liquefaction of natural gas with use of minimum amount of energy.

- Heat exchanger representation in process simulation and optimisation are most often:
  - Black or grey boxes that provide the process input/output states
  - Some degree of ”zone-analysis” in a simplified manner
  - Using lump, composite warm and cold streams

Process optimisation – use of detailed heat exchanger models

- With a detailed heat exchanger model, a chosen design can be validated and the process operability can be investigated
- The heat exchanger model can be a stand-alone program or, preferably, integrated in a process simulator environment
- The focus of this presentation is to investigate a heat exchanger design in terms of steady state instability, also referred to in literature as: Ledinegg type instability.

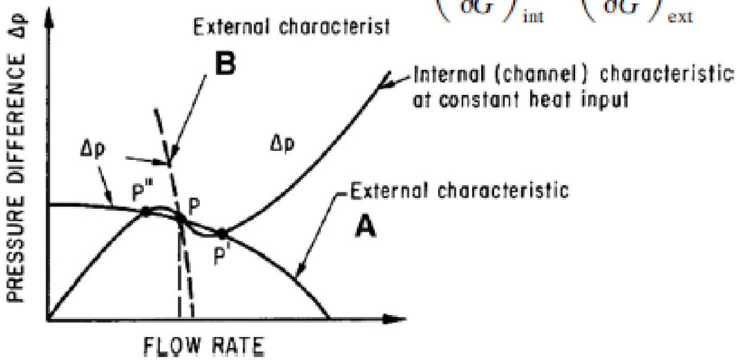
Flow instabilities



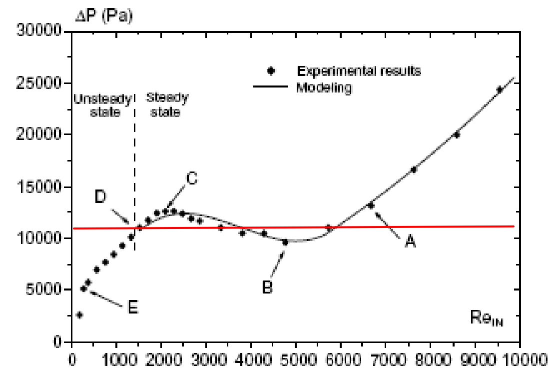
Source:"Review of research on flow instabilities in natural circulation boiling systems" by Prasad G et al, Progress in Nuclear Energy 49 (2007) 429-451

- Ledinegg instability in hydraulic system

$$\left(\frac{\partial \Delta P}{\partial G}\right)_{\text{int}} \leq \left(\frac{\partial \Delta P}{\partial G}\right)_{\text{ext}}$$



- Ledinegg instability in heat exchanger system

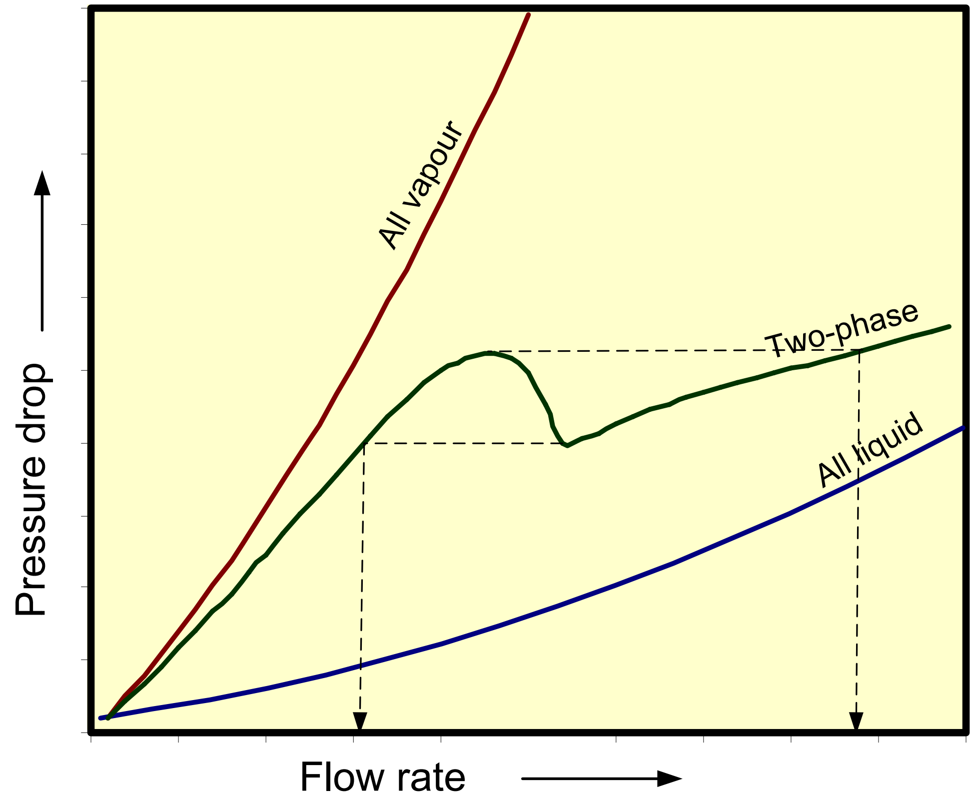


Ref: Brutin and Tadrist: *Pressure drop and heat transfer analysis of flow boiling in a minichannel: influence of the inlet condition on two-phase flow stability*, Int. J.of Heat and Mass cTransfer 47(2004) 2365-2377

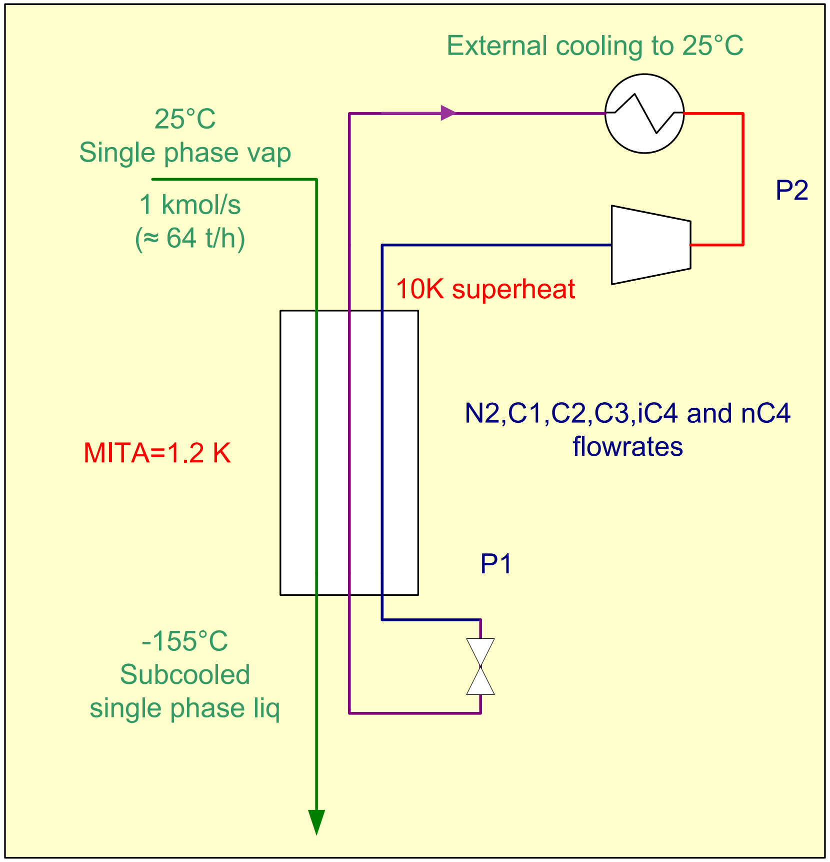
Ledinegg instability in boiling services

- An *N*-shape may occur in boiling services if an increase in flow rate results in a decrease in pressure
- Counteracting effects:
  - Increase in flow -> higher pressure drop
  - Decrease in average void fraction -> lower pressure drop
- Combination: increased flow -> decrease in average void fraction may give an N-shape

N-shape for upward boiling in a heat exchanger



Case: Optimised PRICO process for liquefaction of natural gas



- Cooling and liquefaction of 1 kmole/s NG from 25 to -155 °C
- Optimisation of flow-rate, composition, and pressure levels to obtain minimum energy consumption with restrictions:
  - 10 K superheat
  - 1.2 K minimum temperature approach (MITA)

  With specifications:
  - External cooling to 25°C
- Composition and specification for the natural gas from Jensen and Skogestad (2006)

Ref: Jensen, B.K and Skogestad S, *Optimal operation of a simple LNG process*, ADCHEM 2006

Tools used in this analysis

- Aspen HYSYS® with a separate SQP routine for optimisation

- Sophisticated heat exchanger model – implemented in a process simulation environment
  - S-FIN for PFHE (in-house) - similar to Aspen MUSE
  - The in-house model is available as dynamic link libraries for use in Pro/II by SIMSCI

Description of the S-FIN model

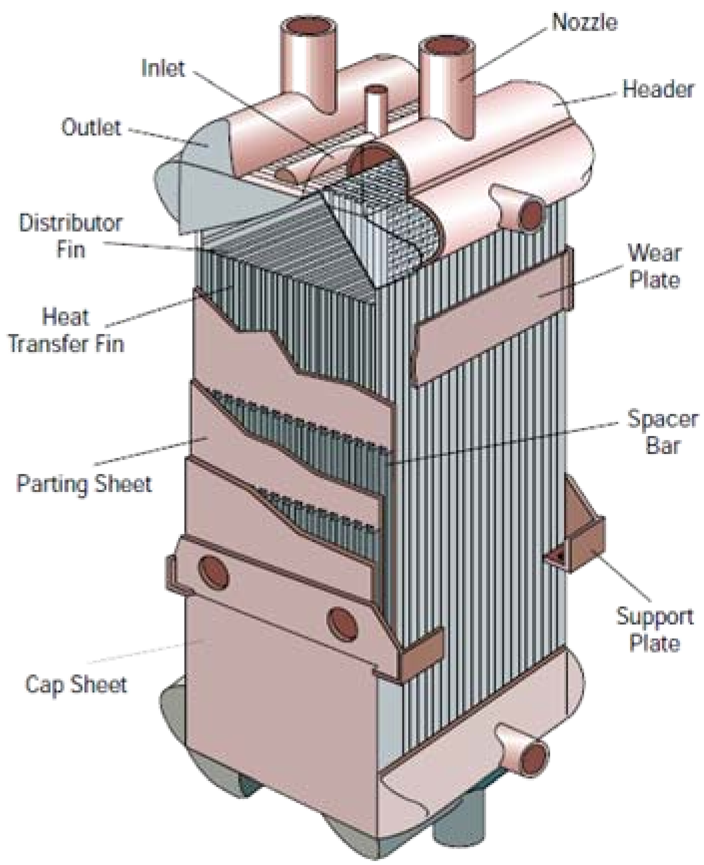
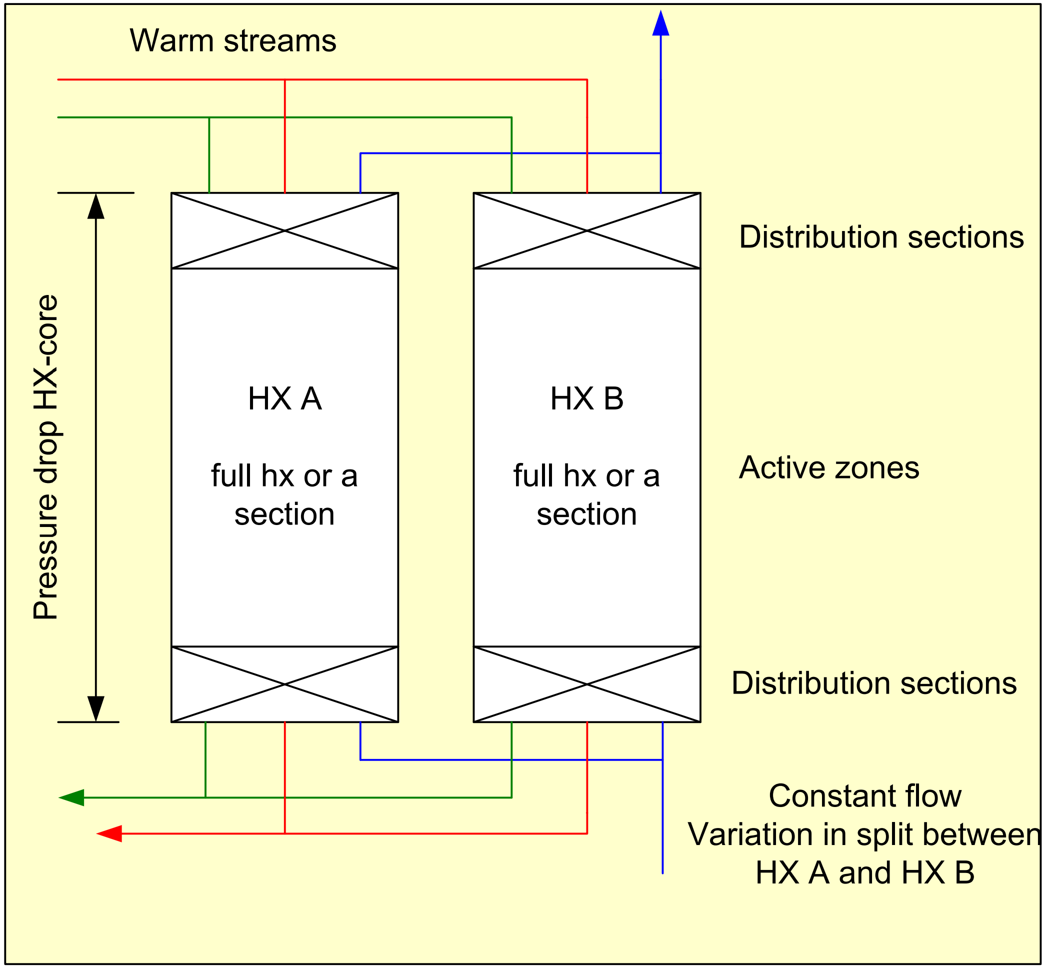


Illustration of a Plate-fin Heat Exchanger from:A ChE's Guide to CHEs.
Vishwas Wadekar, Chemical Engineering Progress, 12(2000)

- User defined geometry characterized by fin type and fin geometry
- Common wall temperature (on same height)
- Streams can have different active lengths, but limited to counter or parallel flow
- Calculation of heat transfer and pressure drop locally for each stream
- Heat transfer calculations is limited to the core only

Principle for analyses with S-FIN



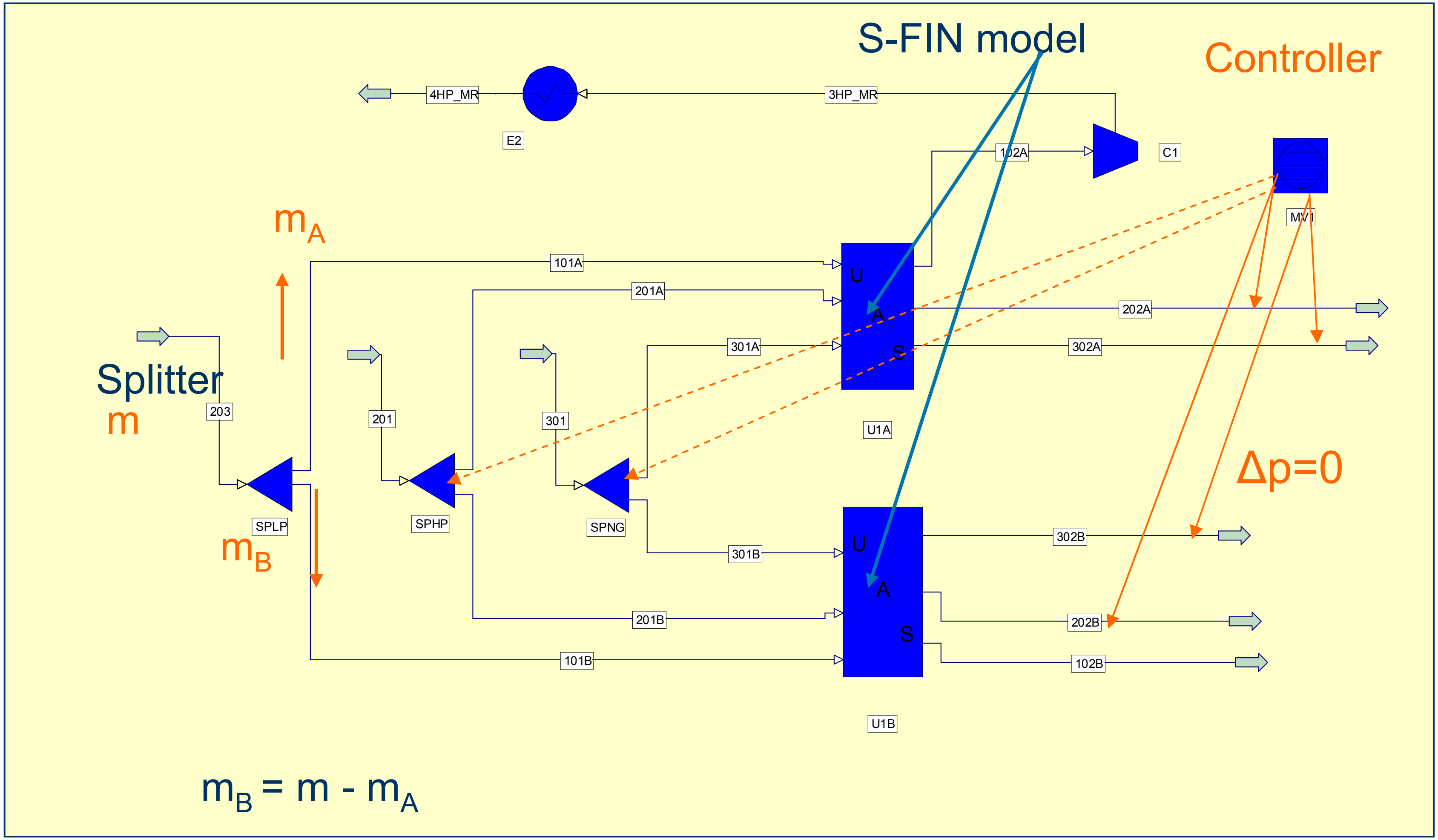
S-FIN can not simulate the Ledinegg instability conditions within one module

Two parallel modules are used

Variations of the split factor for flow between HX-A and HX-B

The corresponding pressure drops are recorded

Principles for Pro/II – S-FIN modelling



Heat exchanger analysis methodology

A: Optimised process parameters

- energy consumption: XX kwh (/ kg LNG)

B: Design a heat exchanger according to optimisation results – evaluate the design

- may need to alter process parameters to avoid temperature crossings
- energy consumption YY kwh / kg LNG

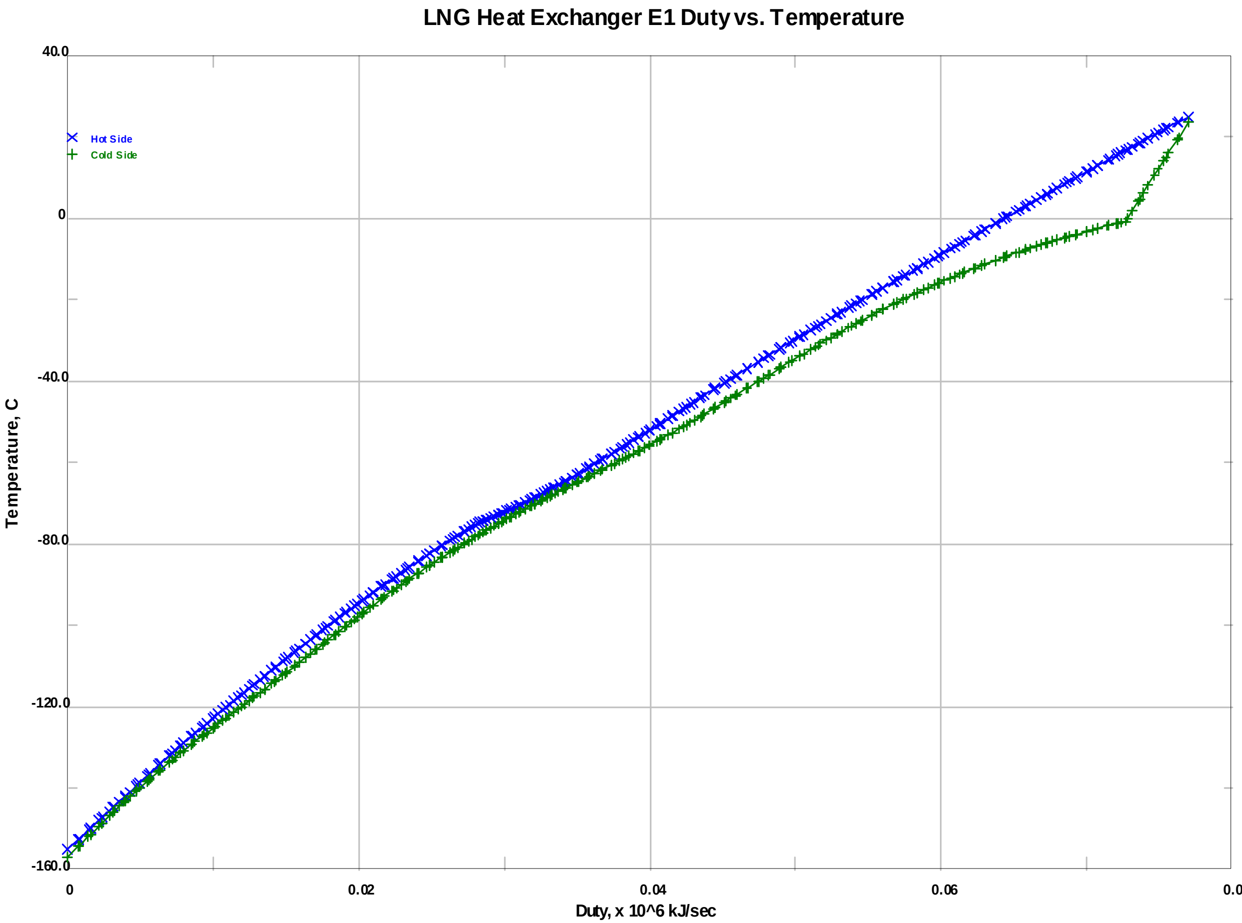
C: Analyse chosen HX design in terms of operability

- may need to alter hx and/or process design
- energy consumption: ZZ kwh/ kg LNG

In most cases: ZZ > YY > XX

A: Optimised process design:

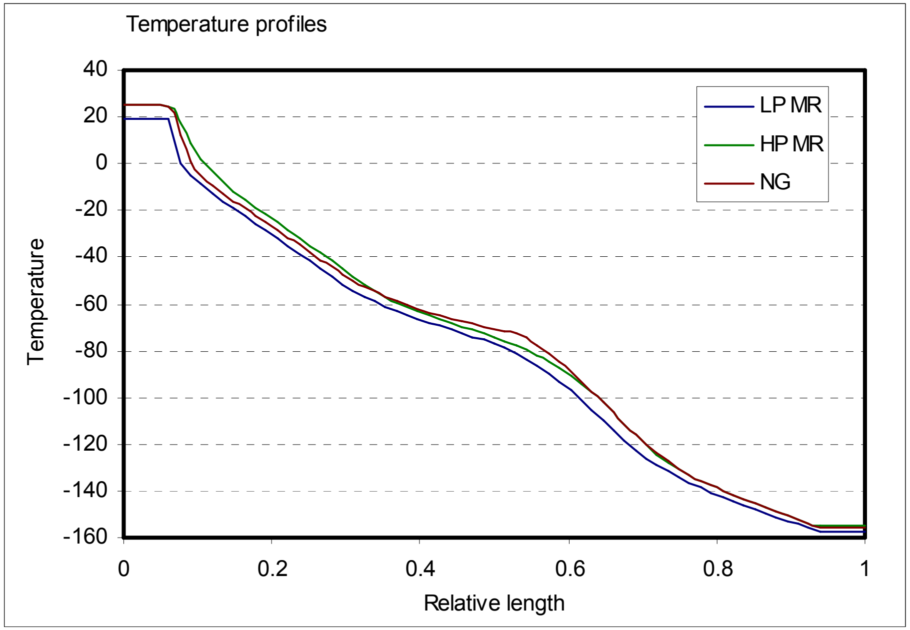
Minimum temperature approach (MITA) = 1.2 and 10° superheat

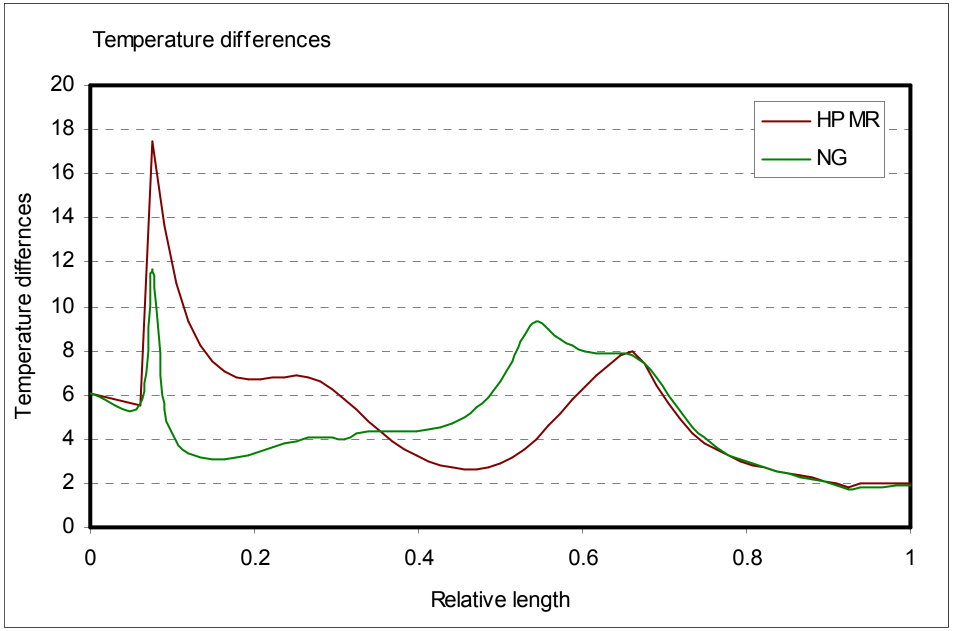


	FULL PRICO
T NG	-155
T LP	-157.1
P LP	5.34
P HP	25.88
N2	0.0929
C1	0.2913
C2	0.3887
C3	
iC4	
nC4	0.2271
MREFR (kmol/s)	3.15
MNG	1

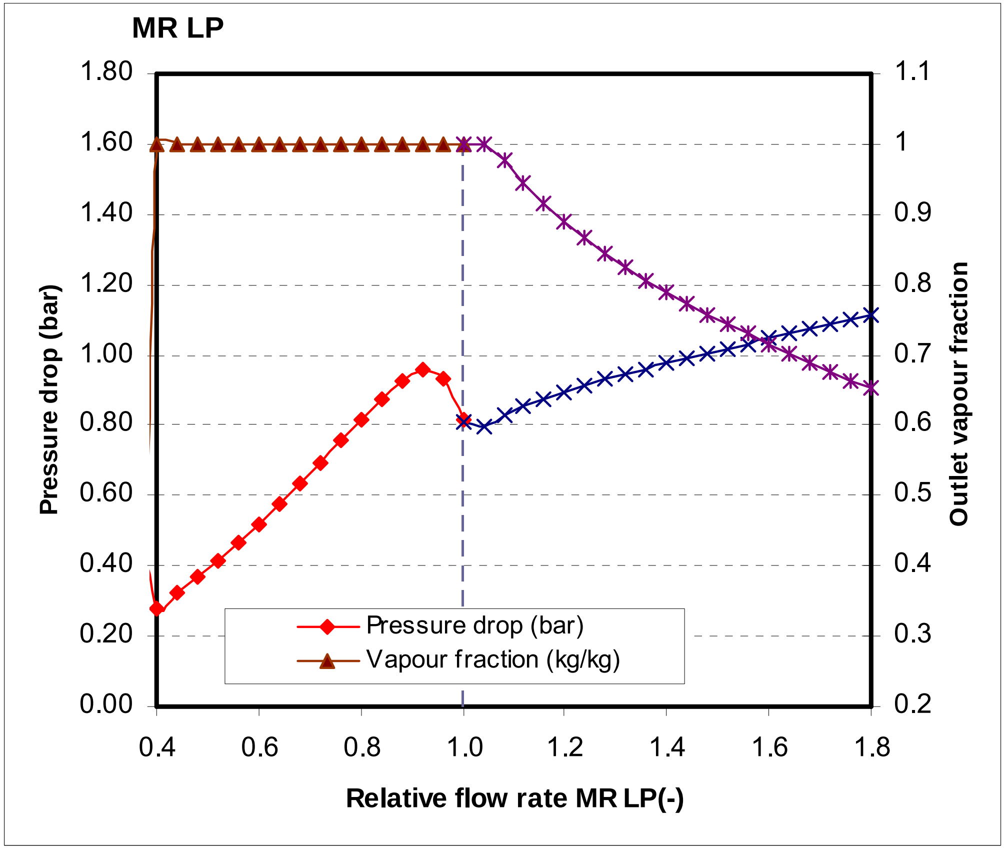
B: Design a heat exchanger

"A few" designs tested –
To avoid temperature crossings, a "long and narrow" design was required





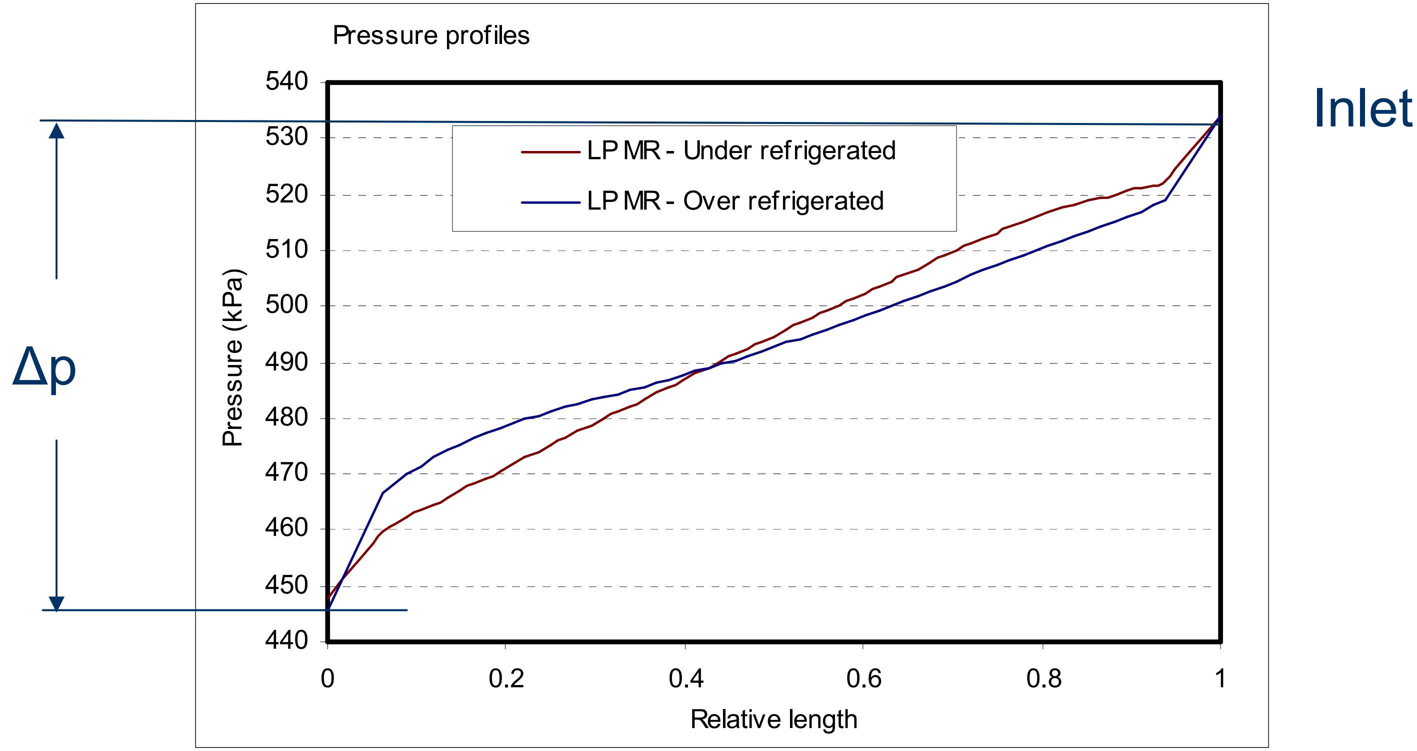
C: Check for operability (N-shape)



Assumption:
Constant warm stream flow rates

Consequences of Ledinegg instability

Equal cold stream pressure drop with flow-rate split 42/58

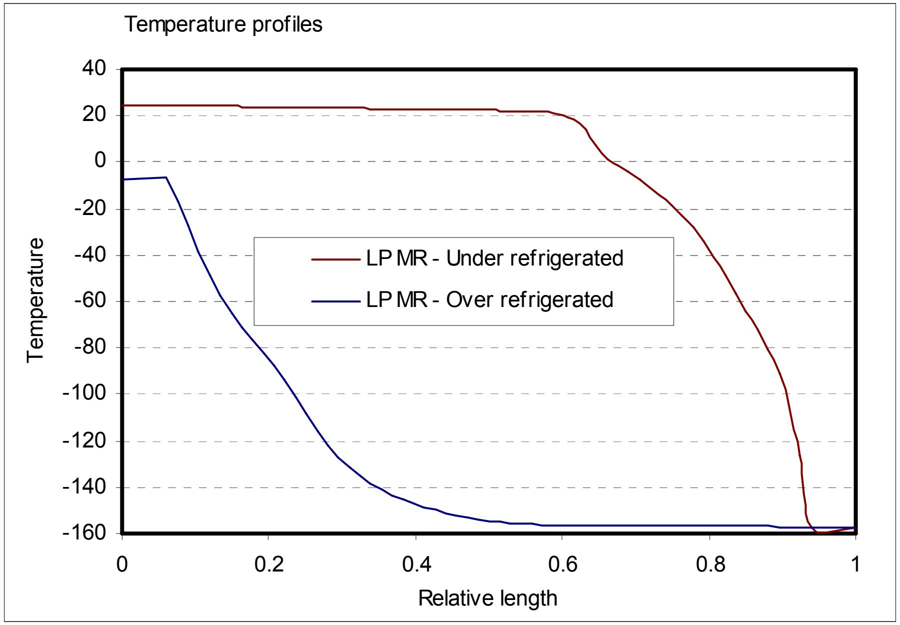


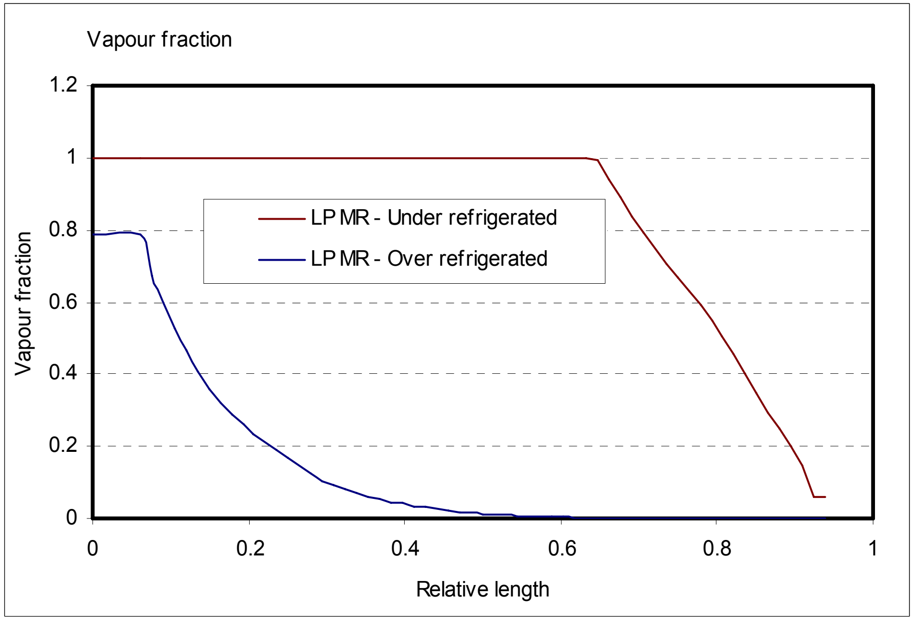
Under refrigerated: Too little refrigerant for current heat load

Over refrigerated: Too much refrigerant for current heat load

Consequences of Ledinegg instability

Equal cold stream pressure drop with flow-rate split 42/58

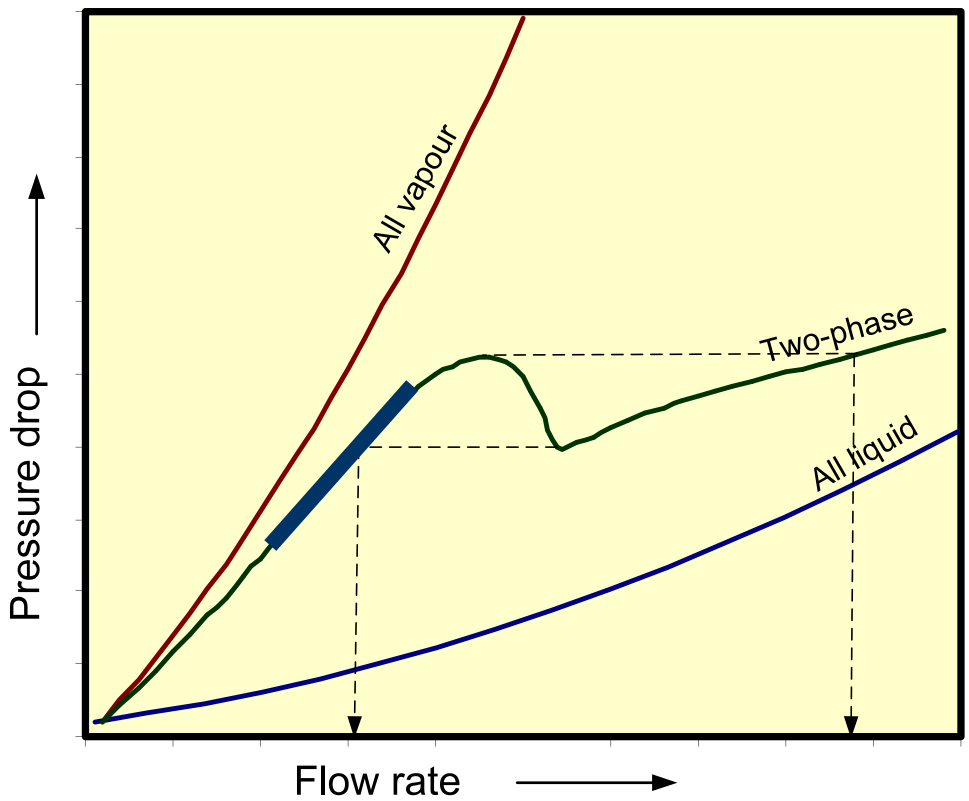




Individual temperature and vapour fraction profile

Remedies for avoiding Ledinegg instabilities

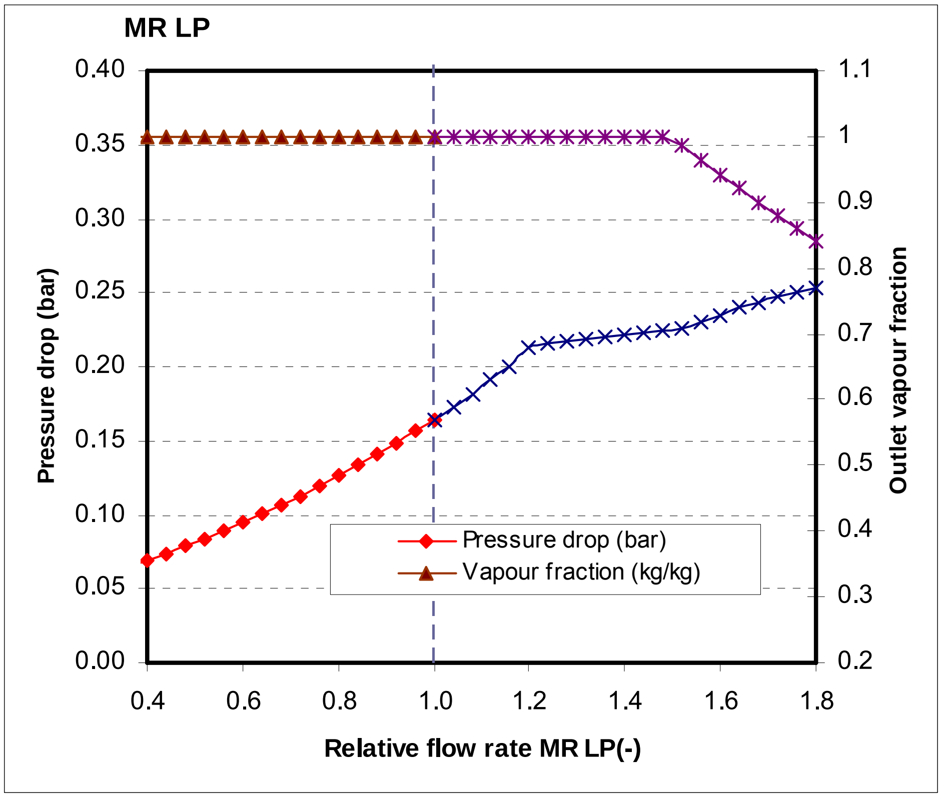
N-shape for upward boiling in a heat exchanger



- Move the operating point within the blue line.
- Get rid of the *N*-shape
  - Modify HX design,
  - Reduce outlet resistance
  - Increase inlet resistance
  - Avoid cold end pinch

Example on modified design

- Reduced heat flux for cold channels – increased surface while maintaining - or reducing the pressure drop…



	HX 1	HX 2
Core volume (m3)	31.7	107.0
Heat transfer surface (m2)	26502	70255
Average heat flux (W/m2)	2911	1073
Mass flux (kg/m2 s)	62.7	19.4
Design pressure drop (bar)	0.82	0.17
N-shape	Yes	No

Conclusion:

- In cryogenic processes using fluids with low density and low latent heat, instabilities are more likely to occur
- The risk of ending up with a design operating point in an unstable region is high, if
  - processes are optimised based on composite curves and minimum temperature differences,
  - the pressure drop curve exhibit an N-shape
- When equipment with a high degree of parallelism is used, this could have serious consequences
- During optimisation, constraints reflecting the remedies for avoiding Ledinegg instabilities should be included when possible

- Instability phenomena are currently the subject of several PhD studies at NTNU and is part of the recently started KMB project on ”Enabling low emission LNG Systems” at SINTEF Energy Research