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"Investigation of non-ideal behaviour of plate-fin heat exchangers in LNG services using optimization techniques"

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Contents

FlexHX: A flexible heat exchanger modeling framework

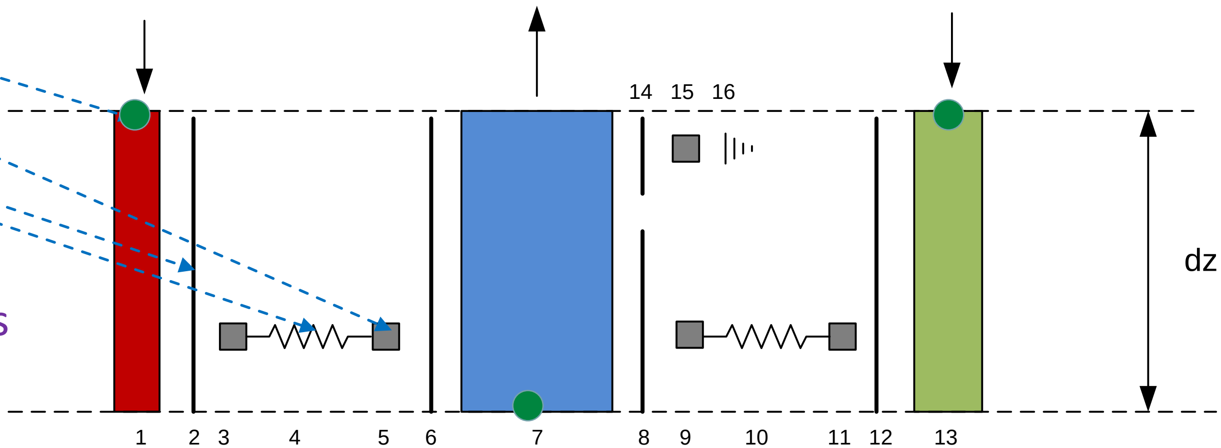
Generic tool with building blocks of:

Heat exchanger elements

- fluid nodes
- heat nodes
- surfaces
- thermal resistors

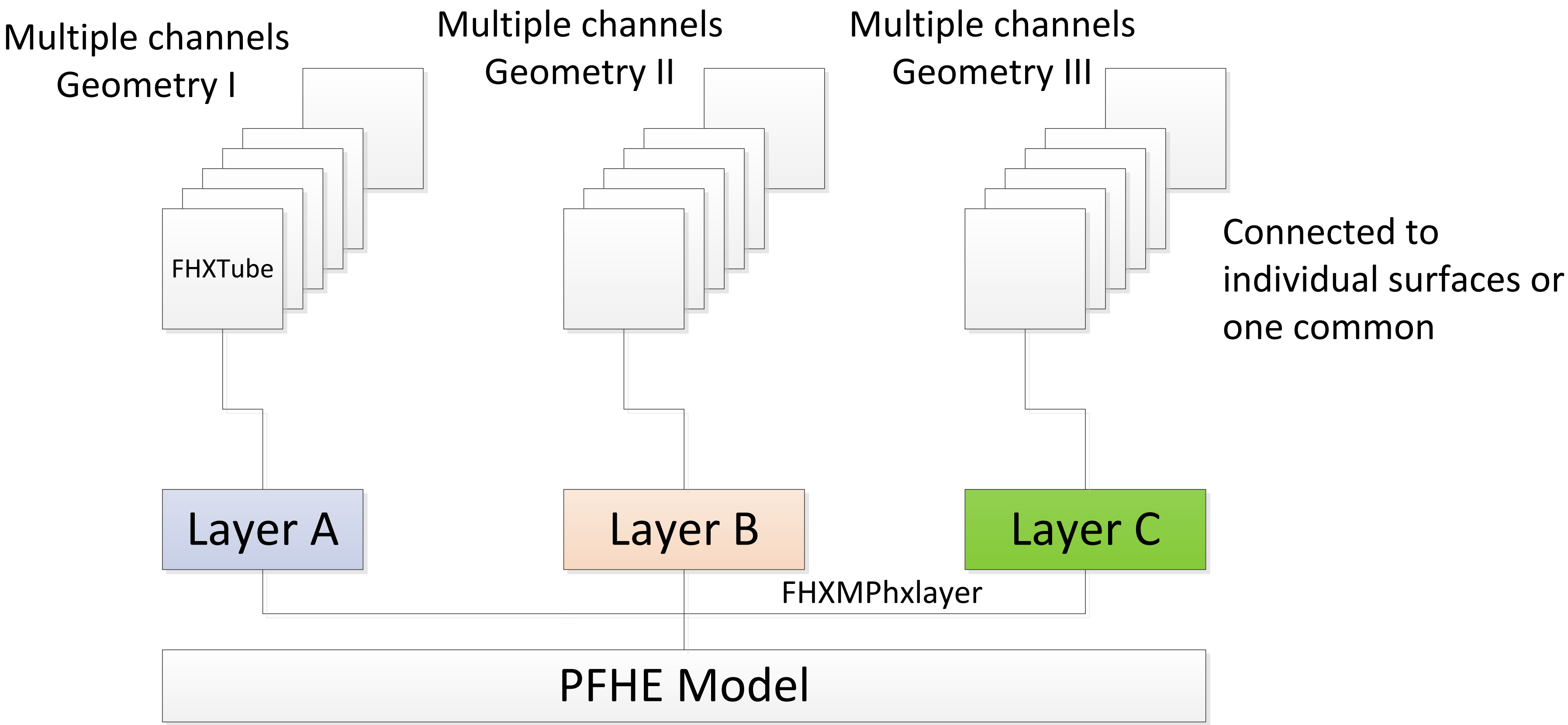
Auxiliary elements:

- headers and distributors
- flow restrictions
- valves
- …

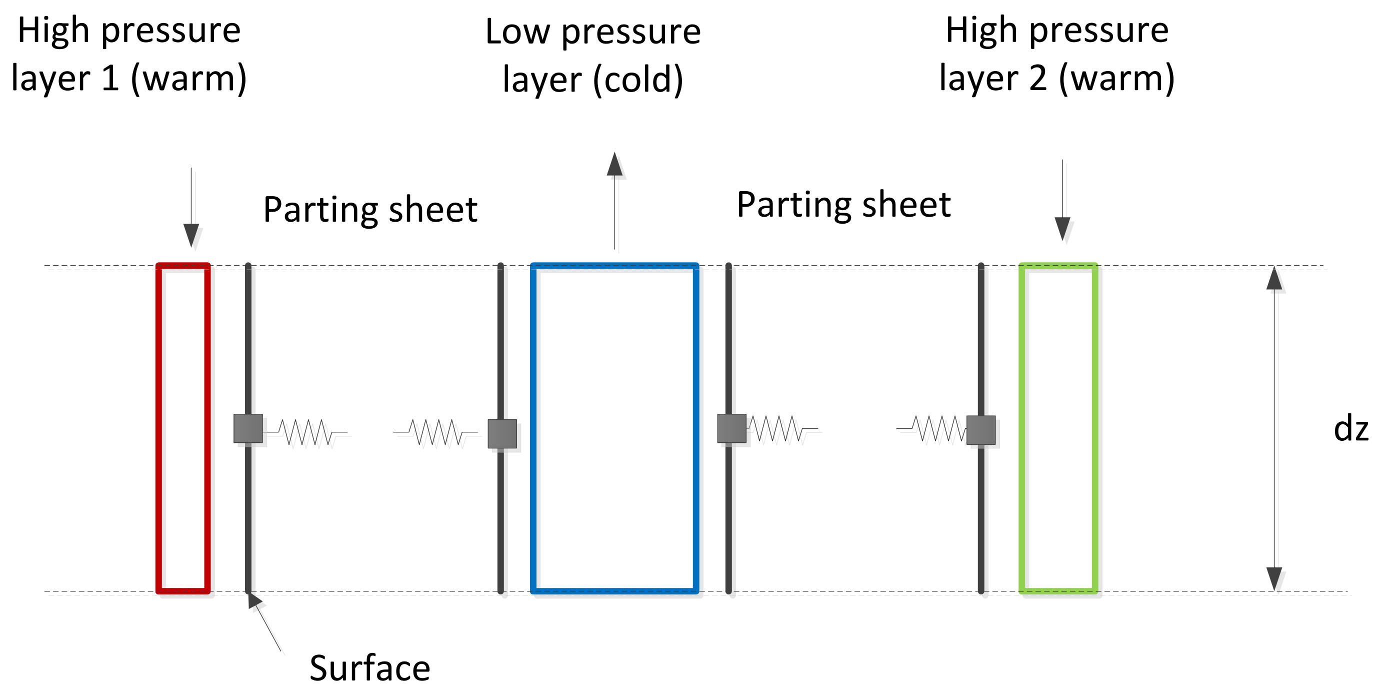


Flexible and robust data structure to handle various heat exchanger variants – both steady state and transient formulation

The Plate-Fin heat exchanger model structure



Simple description of PFHE layers and parting sheets for one heat exchanger element



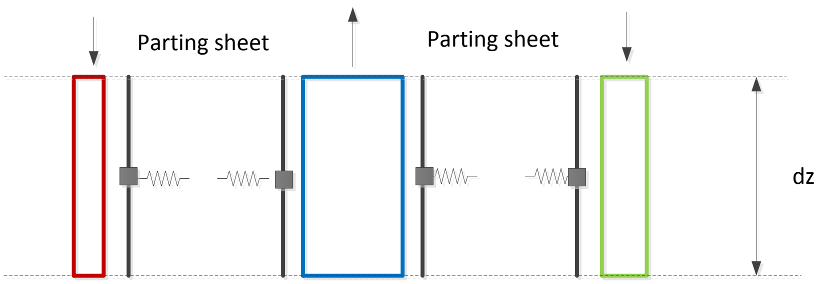
Heat transfer resistance: both axial (conductive) and between parting sheet and fluid (convective + conductive)

Solid nodes representing individual surface (metal) temperatures

Solving the thermo-hydraulic balance in FlexHX

- Guess all metal temperatures
- Integrate
  - Pressure
  - Enthalpy
  - Surface heat transfer

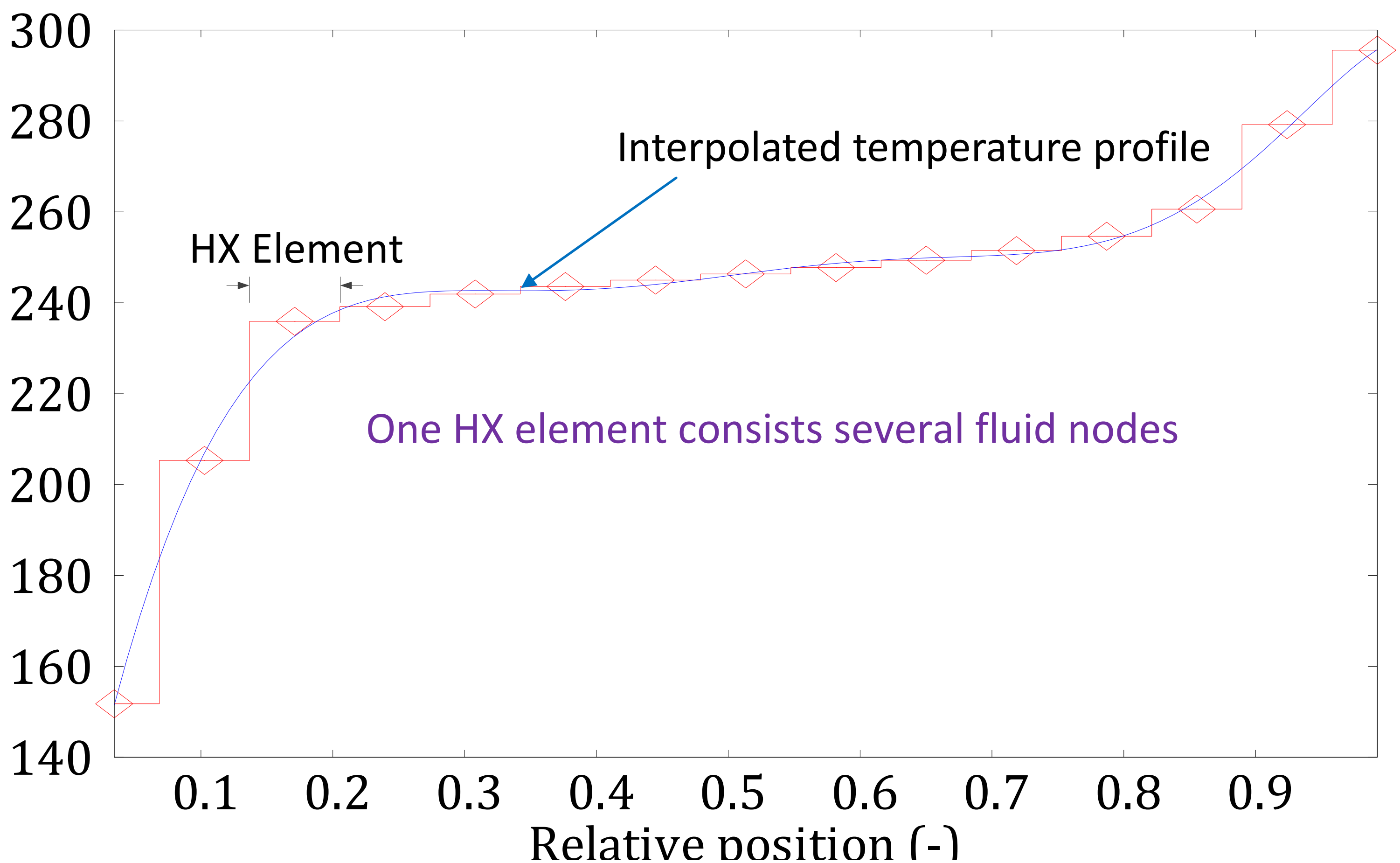
  along each individual fluid pass



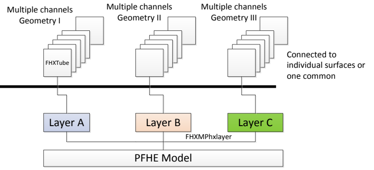
- Solve the heat balances around each solid node temperature as a system of non-linear equations to update all metal temperatures
- The number of thermal equations to be solved: (Streams +1) x (HX elements)

This method has proven to be very robust to handling both phase change and other thermo-physical discontinuities and demanding operating conditions

Wall temperature profile



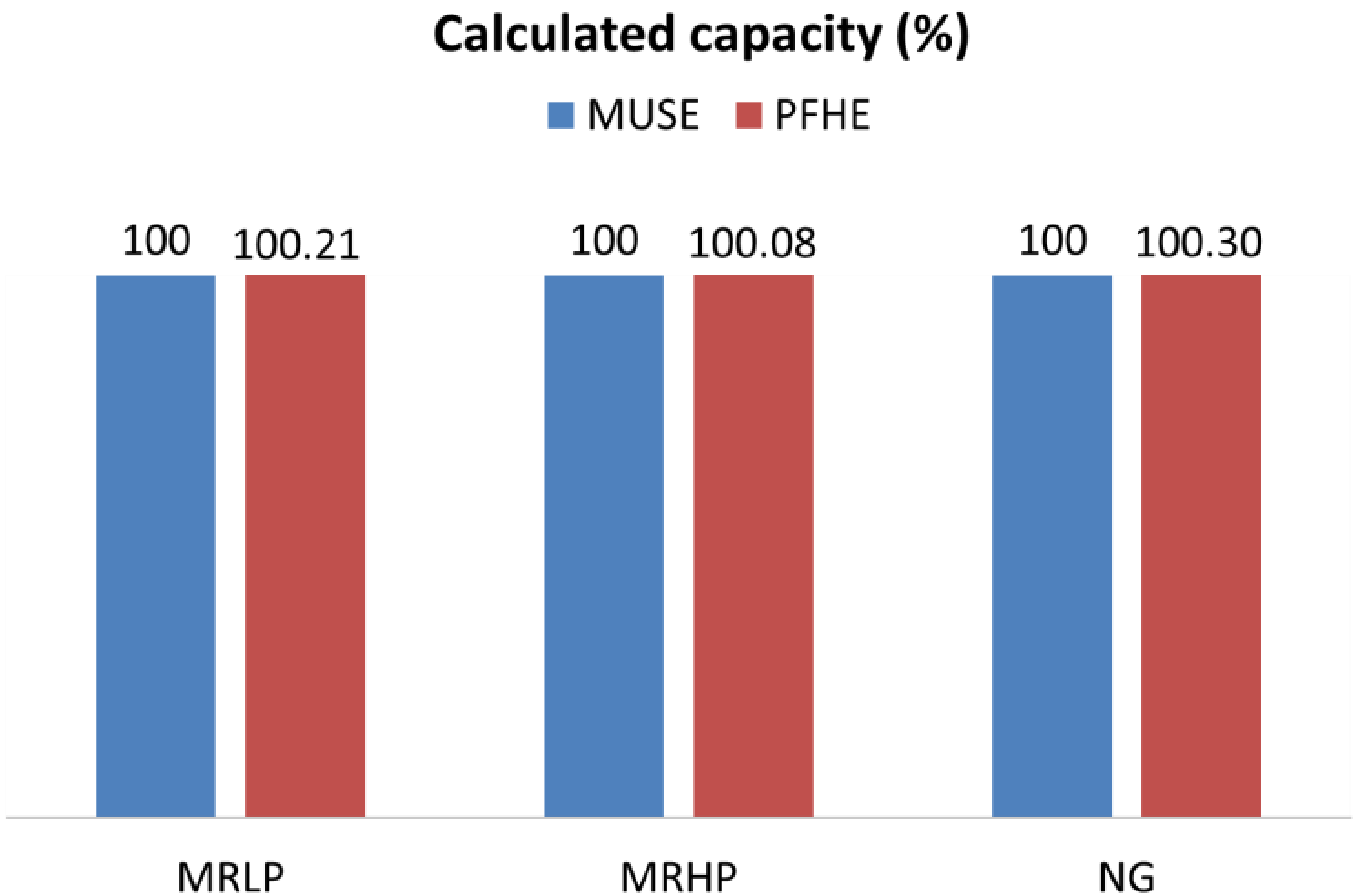
Comparison of the PFHE Model with Aspen MUSE



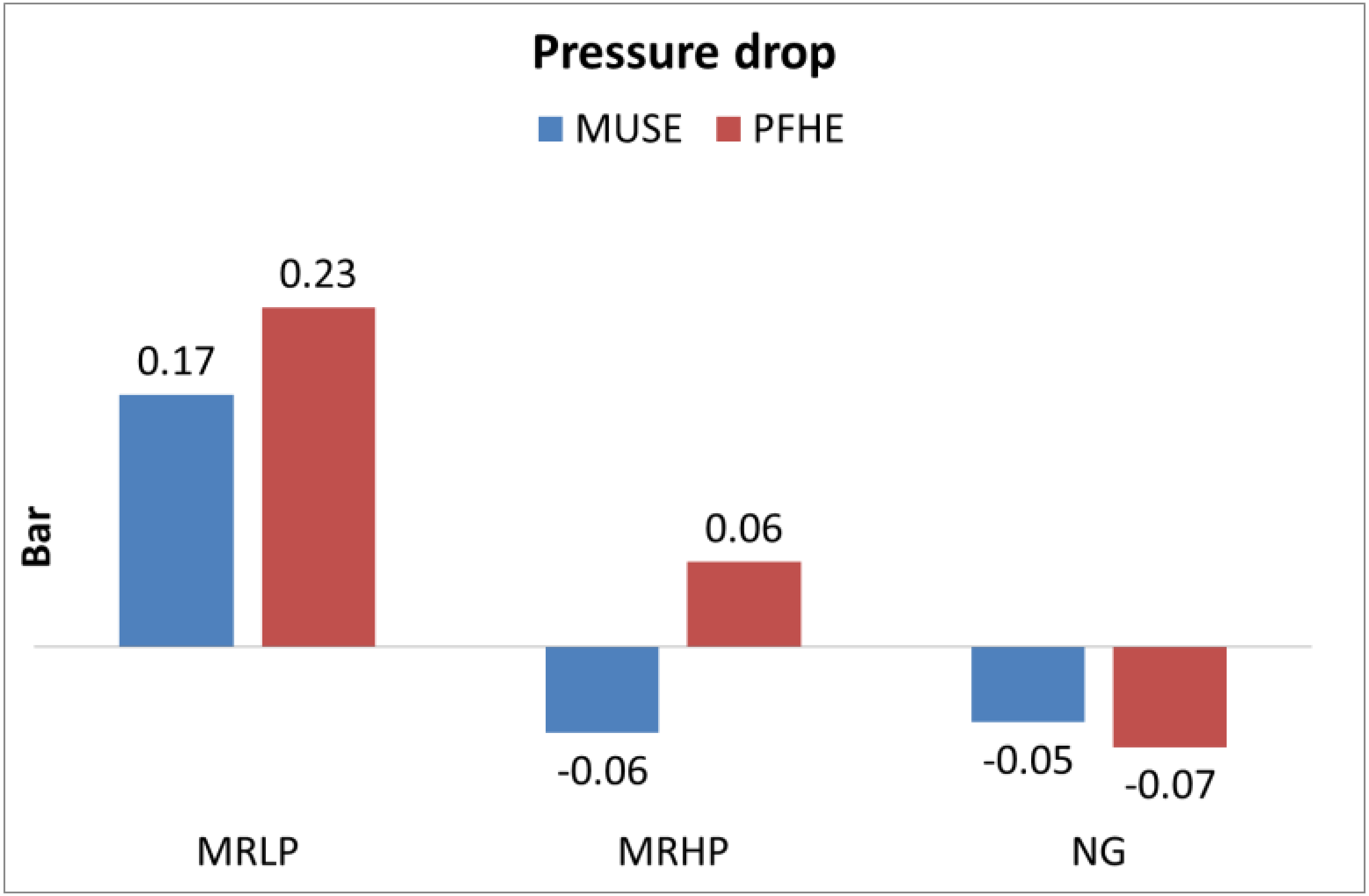
Number of parallel blocks	12
Width (mm) x Depth (mm) x Active length (mm)	1173 x 1272 x 5150

	LPMR	HPMR	NG
Number of layers	1416	720	180
Fin type	Perforated	Serrated	Serrated
Fin height (mm)	5.1	5.1	5.1
Fin thickness (mm)	0.3	0.3	0.4
Fin frequency (m^{-1})	787	787	787
Parting sheet thickness (mm)	2.0	2.0	2.0
Operating conditions :			
Inlet temperature (K)	116.05	298.15	298.5
Inlet pressure (bar)	5.34	25.88	55.0
Inlet vapour fraction (-)	0.0325	0.6656	1.0
Molar flow rate (kg/s)	101.0	101.0	17.7
Mass flux (kg/m^2s)	19.48	33.57	26.76
Flow direction	Upward	Downward	Downward

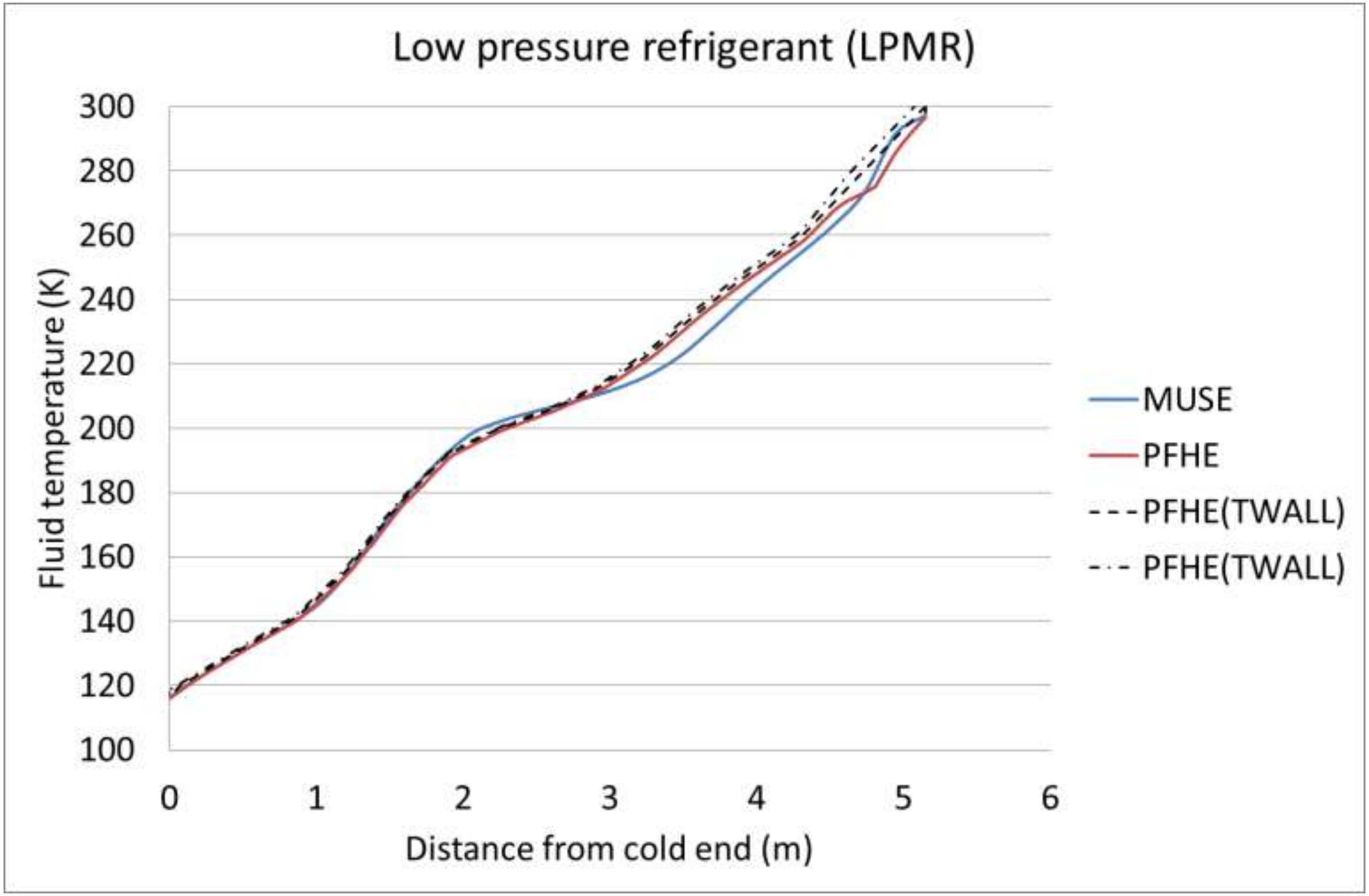
Comparison of capacity between MUSE and the PFHE

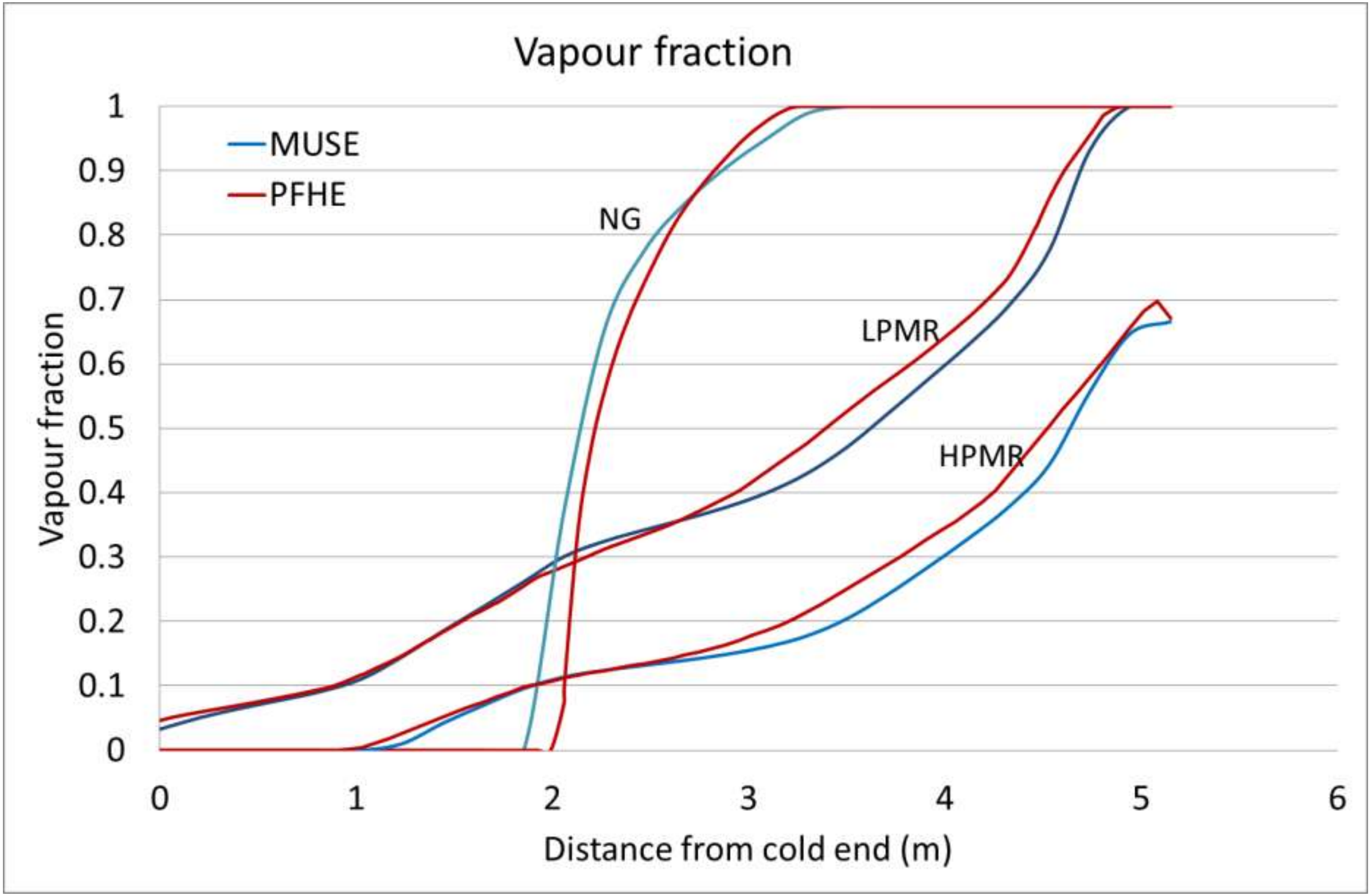


Comparison of calculated pressure drop



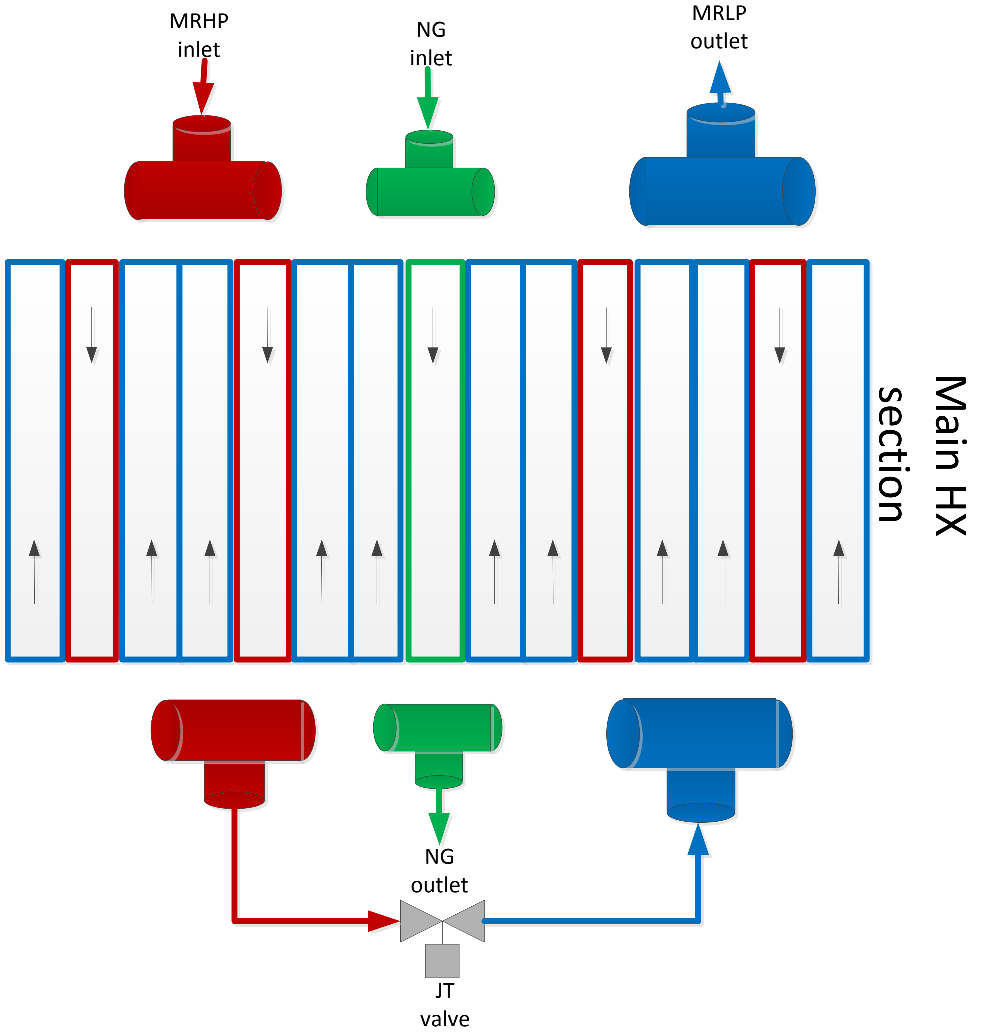
Temperature profile




Vapour fraction
MUSE
PFHE
NG
LPMR
HPMR
Vapour fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
Distance from cold end (m)

Modelling of individual layers

- Individual, local spatial wall temperatures
- Include headers and flow distribution/restriction elements
- Investigate the effect of
  - layer-stacking
  - flow mal-distribution
  - geometry imperfections
- Optionally include the J/T-valve between high pressure and low pressure refrigerant



Inclusion of flow distribution equations

Pressure drop and flow distribution are influenced by:

- Difference in heat flux in individual layers
- Individual flow lengths through distributors
- Geometrical imperfections

Equal pressure drop for each individual layer for each stream

$$\sum_{i=1}^{\mathrm{ns}} \sum_{j=2}^{\mathrm{nl}(i)} \Delta p_{i,j} - \Delta p_{i,1} = 0$$

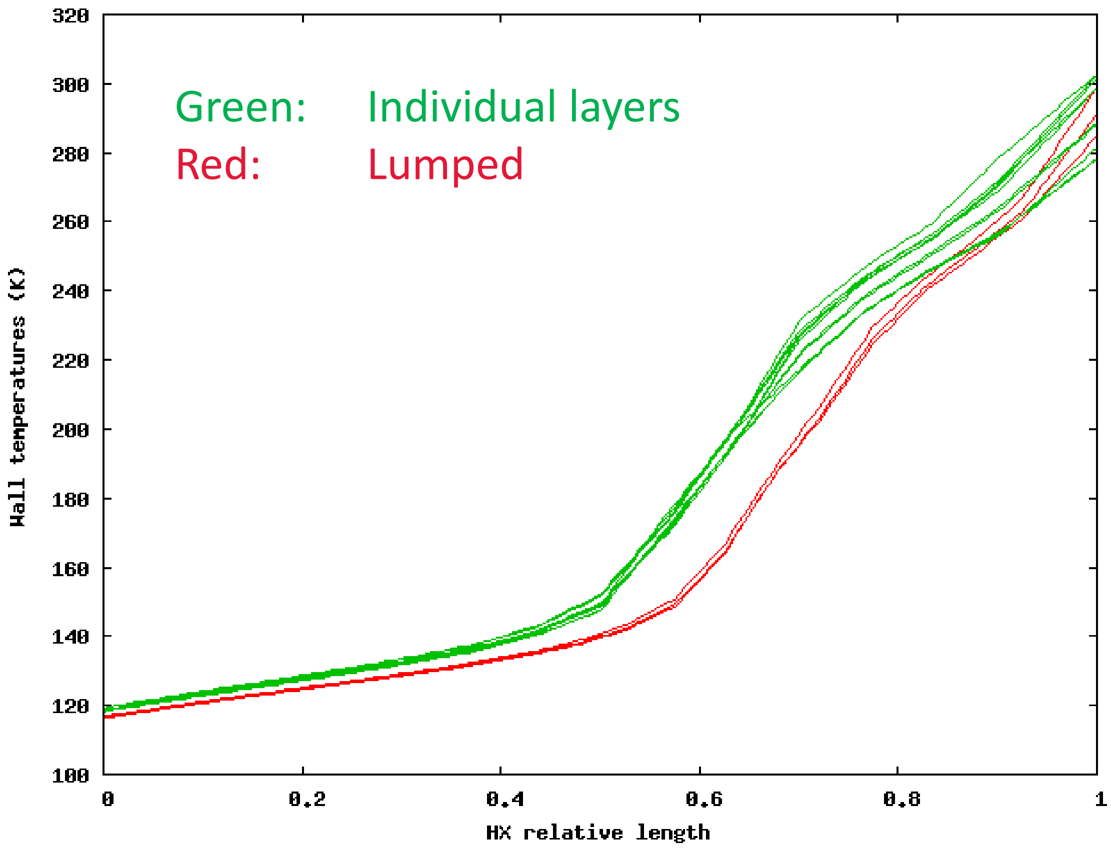
Sum of individual flow rates in each layer is equal to the stream flow rate

$$\sum_{i=1}^{\mathrm{ns}} \left(\sum_{j=1}^{\mathrm{nl}(i)} \dot{m}_j \right) - \dot{m}_i = 0$$

nl: Number of layers
ns: Number of streams

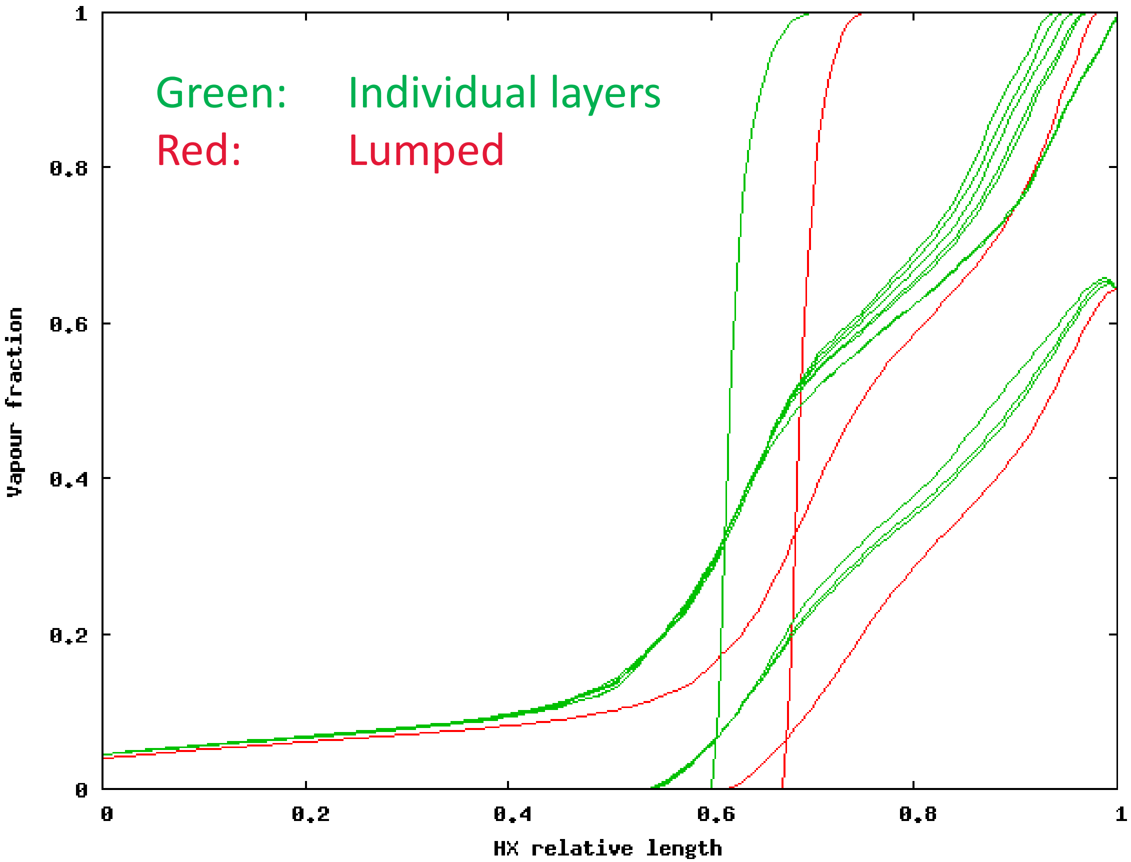
Individual layers vs. lumped-layer-model

Wall temperature profiles



Individual layers vs. lumped-layer-model

Vapour fraction profiles



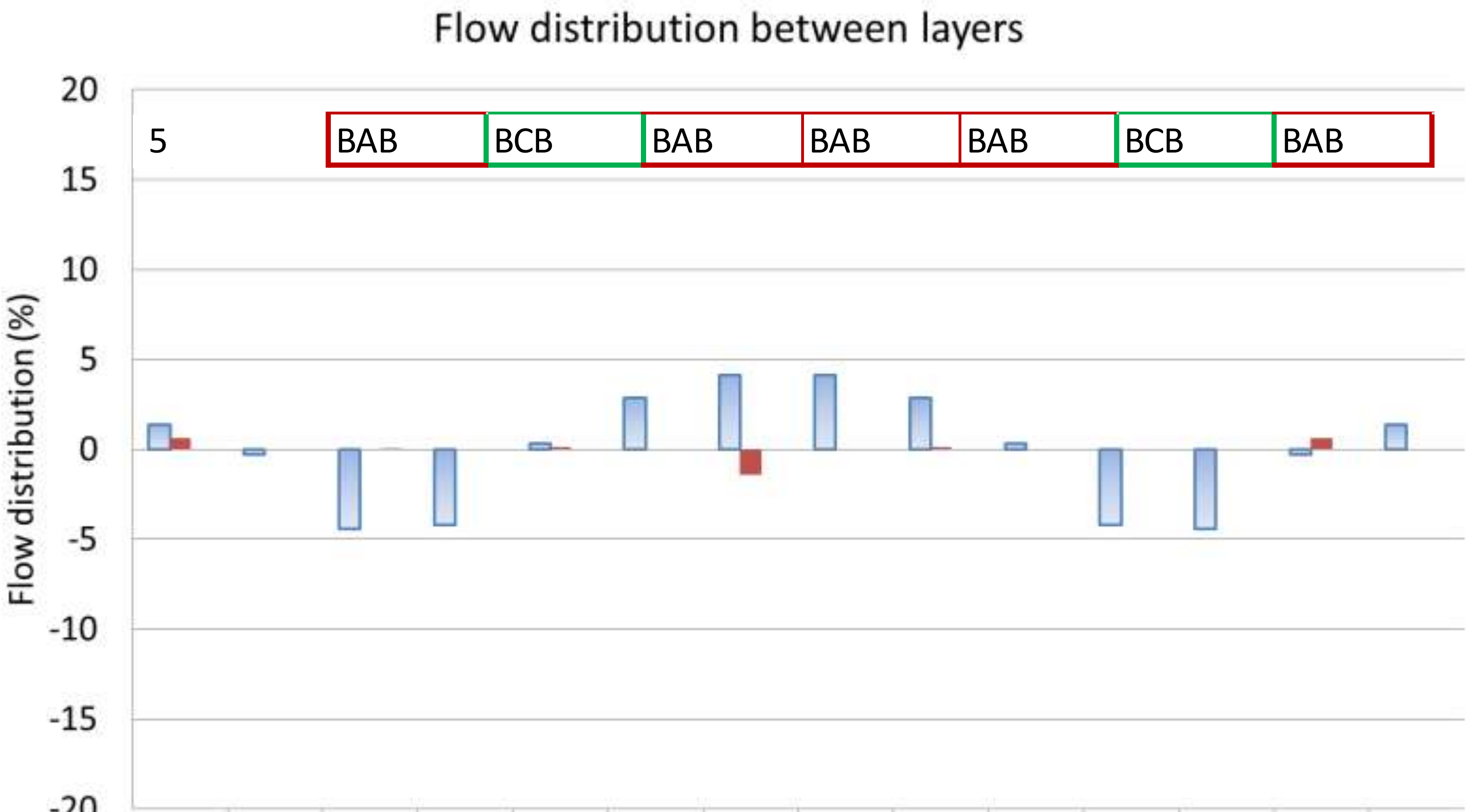
Examples of effects of Layer stacking – 1/20th of full HX

Layer ID	Stream	Number of layers
A	High pressure refrigerant	5
B	Low pressure refrigerant	14
C	Natural gas	2

Possible stacking pattern (scaled down HX)

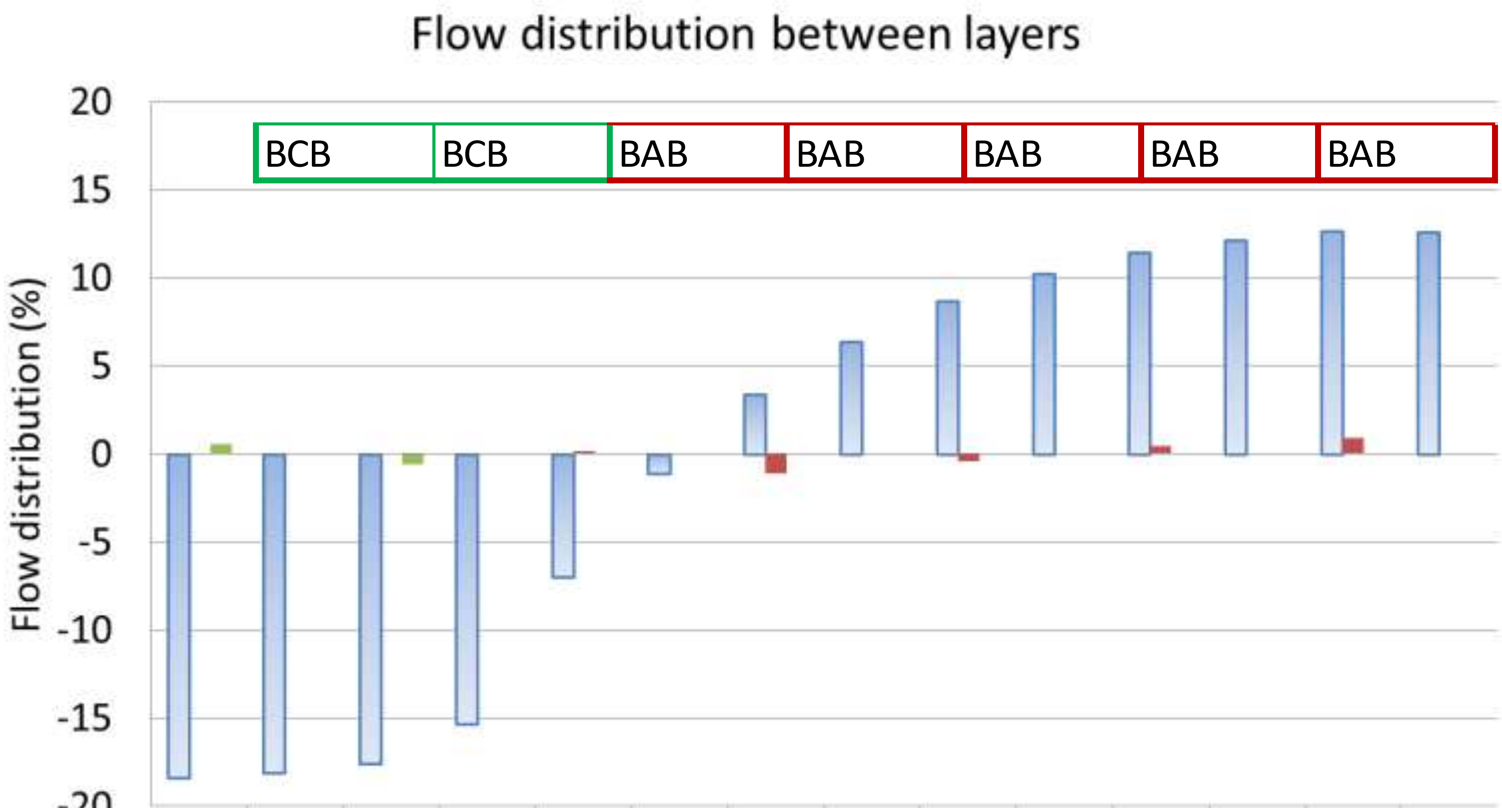
2	BCB	BCB	BAB	BAB	BAB	BAB	BAB
5	BAB	BCB	BAB	BAB	BAB	BCB	BAB

Results from symmetric layer pattern



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MRLP	1.42239	-0.2537	-4.3941	-4.1706	0.33216	2.91223	4.15264	4.15284	2.91243	0.33216	-4.1706	-4.3947	-0.2545	1.42137
MRHP	0.60213				0.11142		-1.4271		0.11142				0.60213	
NG			8.6E-05								-9E-05			

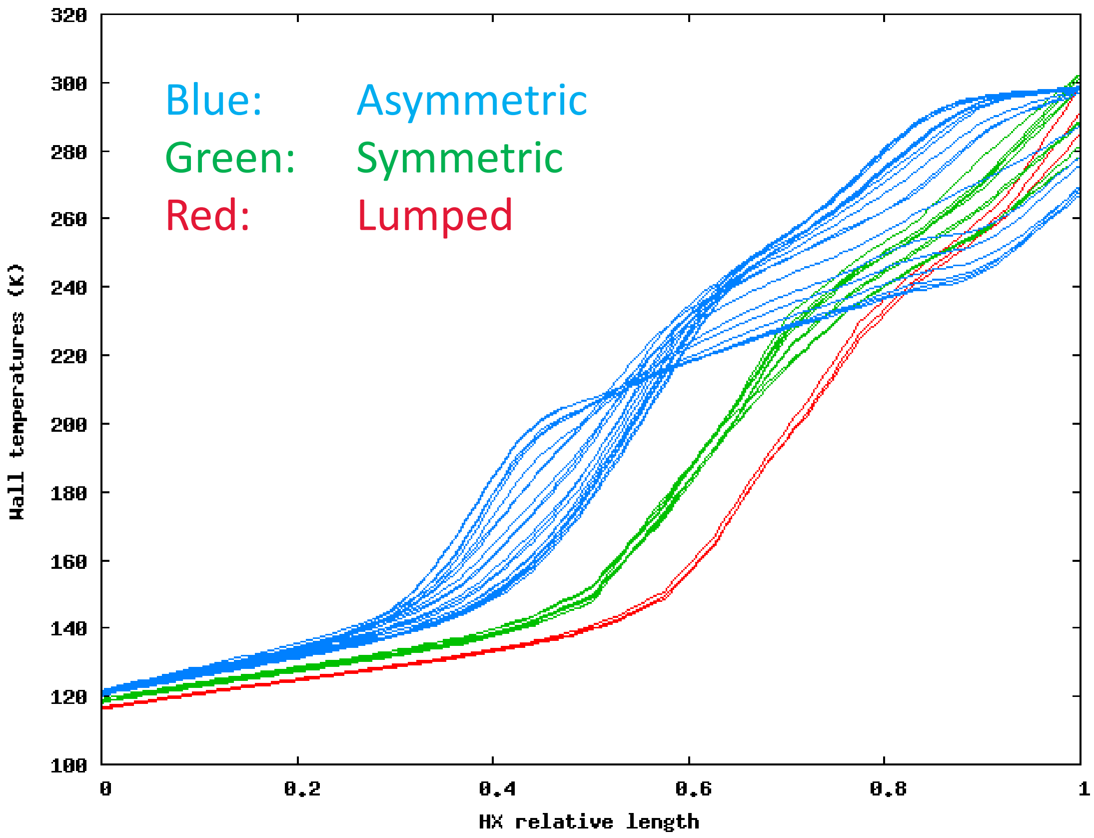
Results from asymmetric layer pattern



	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MRLP	-18.41	-18.11	-17.6	-15.33	-6.997	-1.09	3.3939	6.3732	8.668	10.258	11.437	12.153	12.646	12.602
MRHP					0.1604		-1.101		-0.426		0.4344		0.9318	
NG	0.583		-0.583											

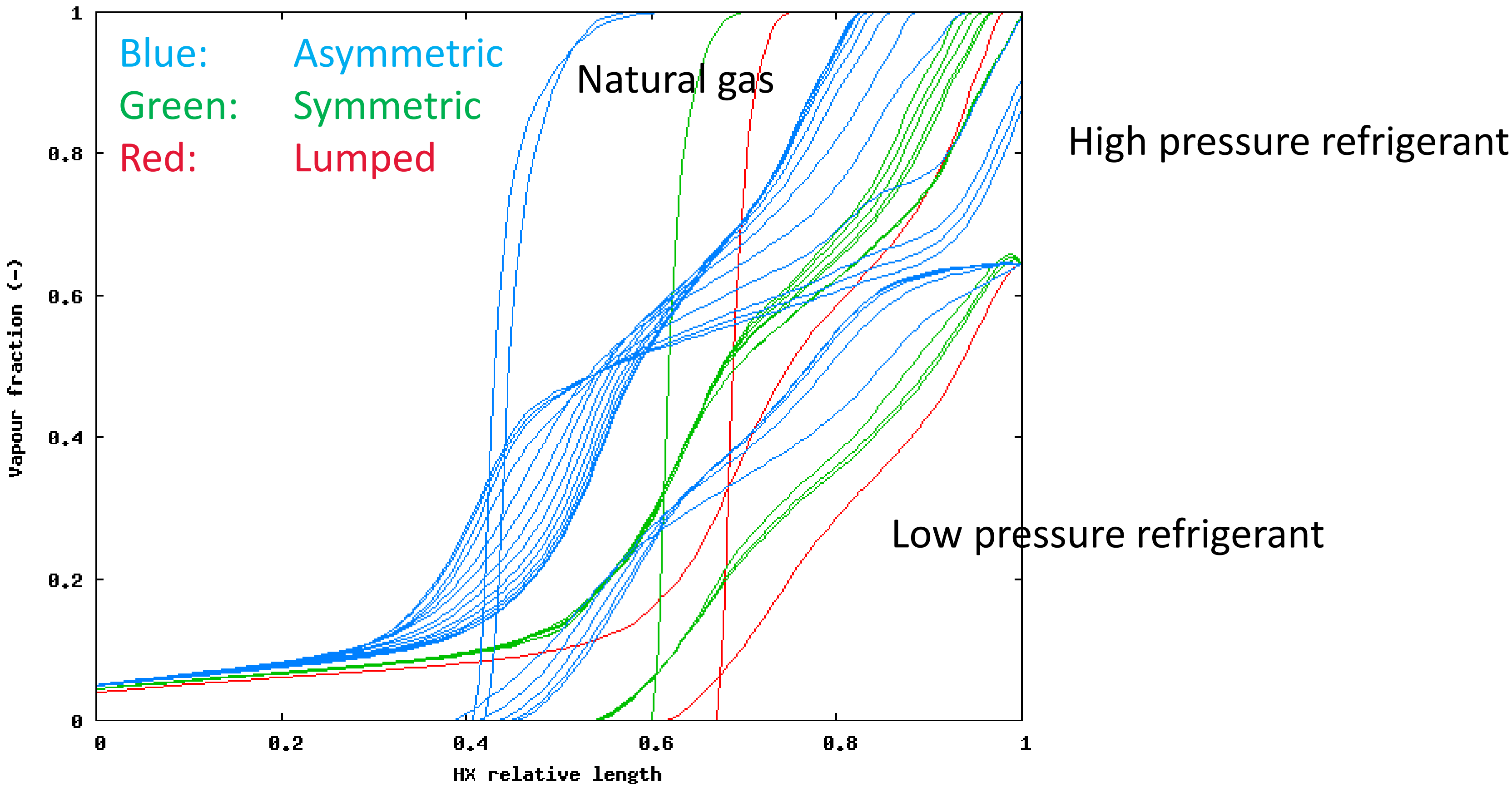
Individual layers vs. lumped-layer-model

Wall temperature profiles



Individual layers vs. lumped-layer-model

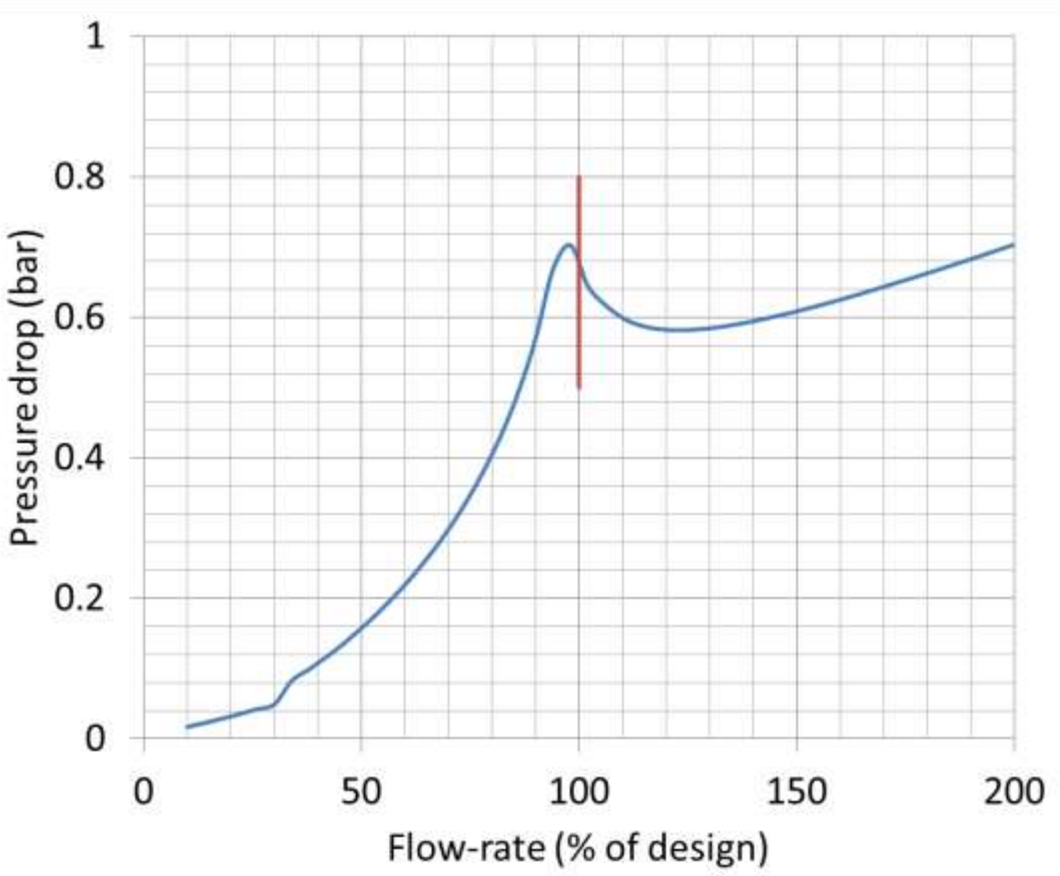
Vapour fraction profiles



Individual layers vs. lumped-layer-model

	Lumped layer model	Individual layer model – symmetric	Individual layer model – asymmetric
Cooling capacity (kW)	1750	1731 (- 1.03 %)	1718 (-1.81 %)
Outlet NG temperature (K)	116.6	118.9 (+ 2.3)	121.2 (+ 4.6)
Required oversizing		22 %	38 %

Investigation of flow instability (Ledinegg instability)



Find the flow mal-distribution that will have the lowest pressure drop

A "reasonable" high number of individual layers are required

Formulation of the optimisation problem

$$\text{minimize } f(\boldsymbol{x})$$

Pressure drop (MRLP)

$$\text{subjected to } g(x_j) = 0, \qquad j = 1 \ldots, m_e$$

Equal pressure drop for each layer

$$g(x_j) \geq 0, \qquad j = m_e + 1 \ldots, m$$

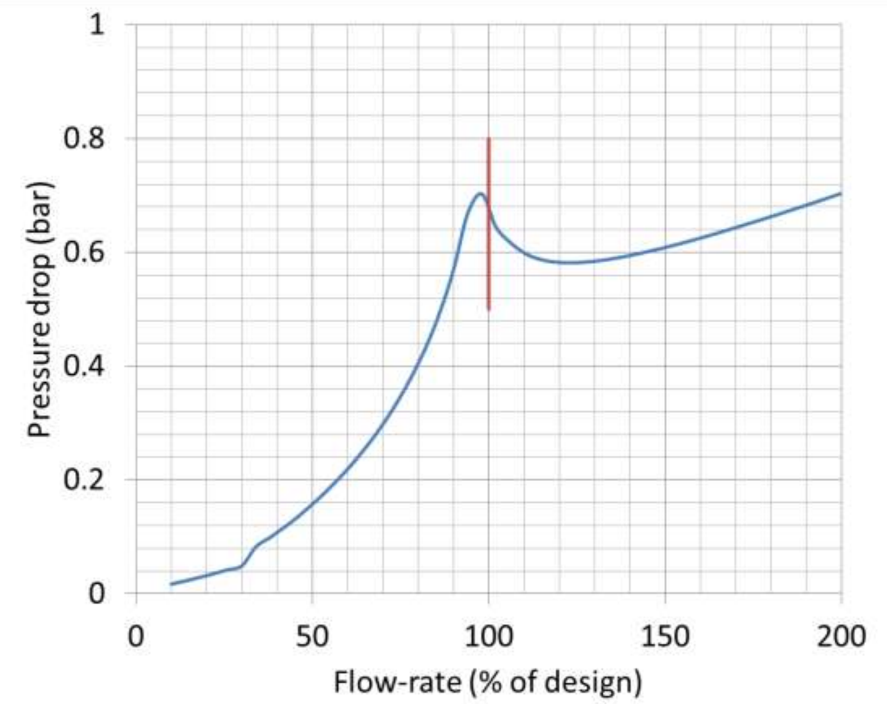
All mass-flows must be positive (other process constraints)

$$x_l \leq x \leq x_u \; \forall \, x_i, i = 1..n$$

A given range for the mass-flow rates

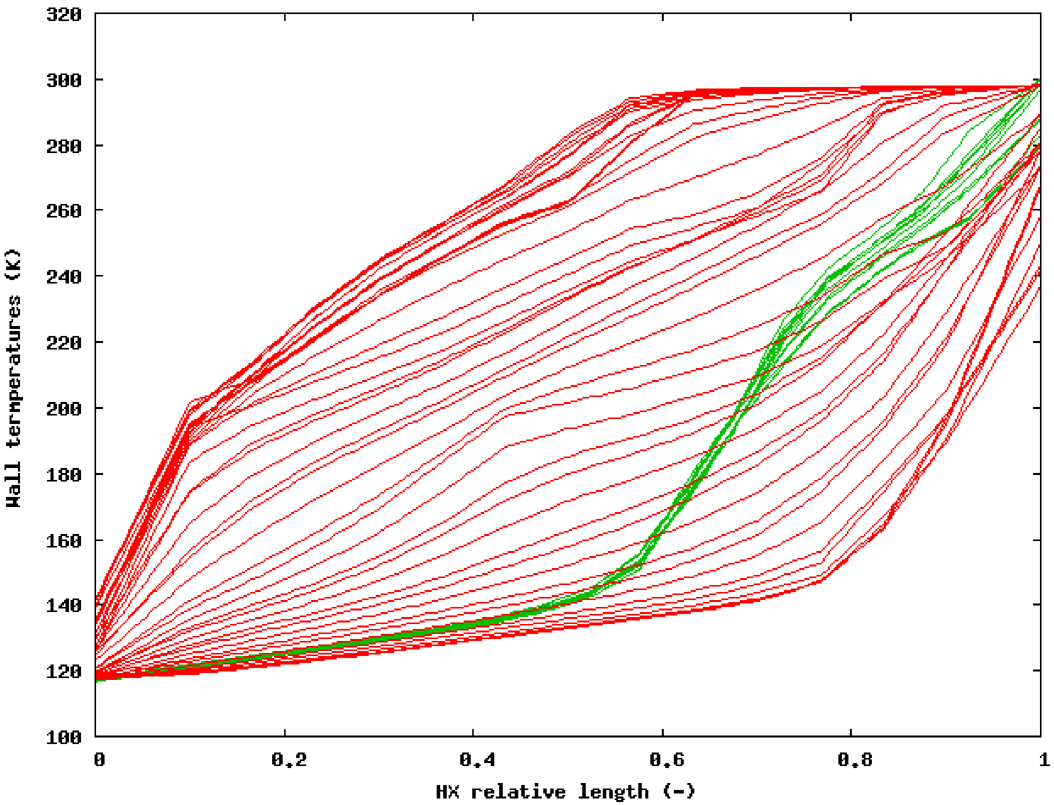
Results from the optimisation

- In the current setup, the number of free variables (flow rates) are equal to the number of equality constraints
- No degree of freedom to "optimize"
- Multiple solutions may exist: Initial values for the individual flow rates determine the solution
- Inequality constraints ensure physical solutions



Results from the optimisation

- The strong thermal coupling through the metal walls ensure low temperature difference between neighbouring streams

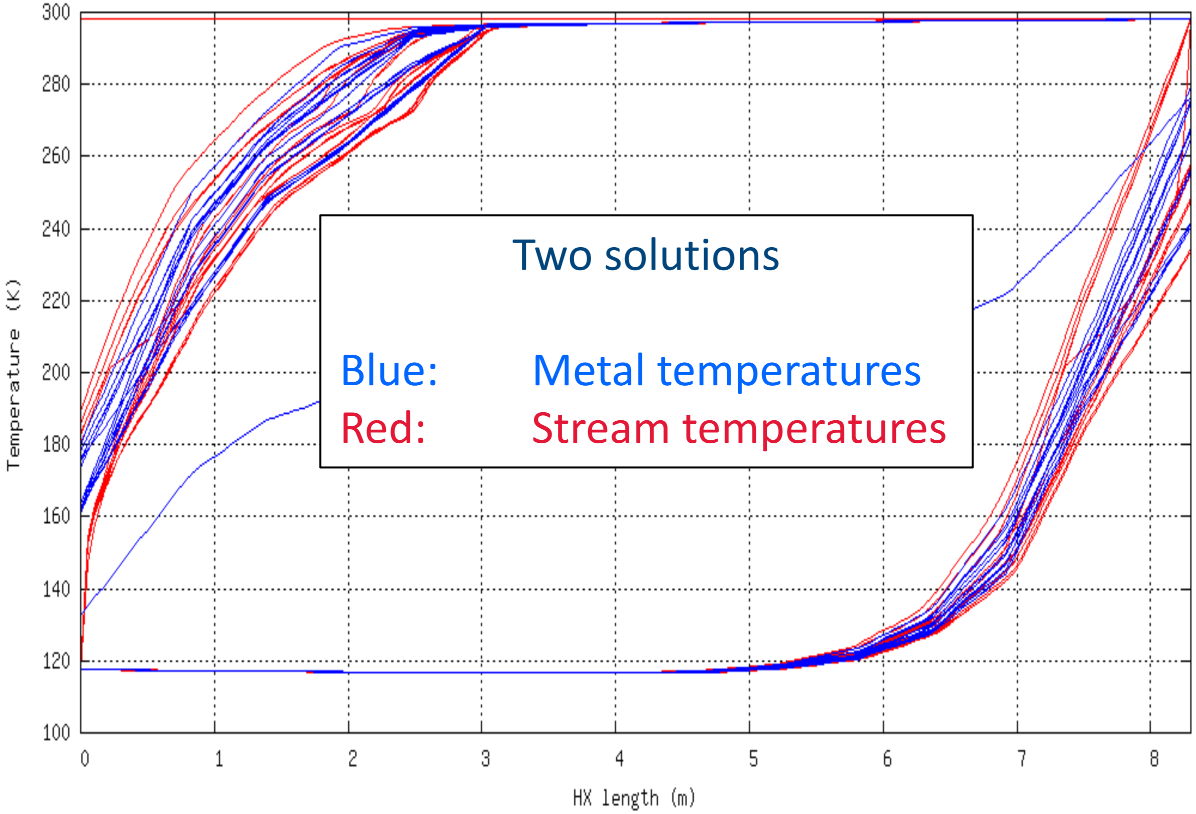


Two solutions:
Plot of metal temperatures:

Green: Equal distribution
Red: Mal-distribution

Results from the optimisation

- Break the thermal coupling by introducing one insulation layer
- Two different solutions can be found
- Cooling capacity is reduced by 15 %



Summary and conclusions

- A detailed Plate-Fin heat exchanger model has been developed in order to investigate effects of stacking pattern and non-ideal behaviour
- Effects of different layer stacking may require oversizing 20-40%
- Strong thermal coupling through the metal walls ensures small local temperature differences
- In a situation where flow instability may occur, two unique solutions for the mass-flow distribution can be obtained – but depending of the initial values
- An additional degree of freedom required for a full optimisation (internal mass-transfer?)
- **Nevertheless**: A design or operating condition where multiple solutions may exist should be avoided

Acknowledgements

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