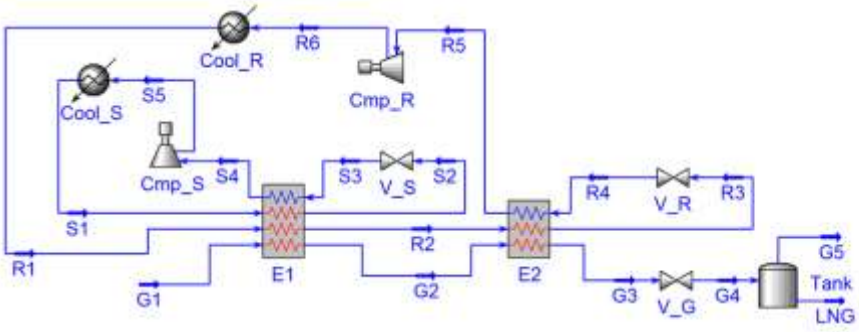


TGTC-3, Trondheim June 5th, 2014

From droplets to process:

Multilevel research approach to reduce emissions from LNG processes

<u>Sigurd Weidemann Løvseth</u>
Ingrid Snustad
Amy Leigh Brunsvold
Geir Skaugen
Per Eilif Wahl


Karl Y. Lervåg


S. T. Munkejord


M. Aa. Gjennestad


Å. Ervik


A. L. Brunsvold


A. Austegard


P. Nekså


Geir Skaugen


I. Snustad


G. A. Reigstad


T. Flåtten


A. Morin


T. Ytrehus


Ø. Wilhelmsen


P. E. Wahl


B. Austbø

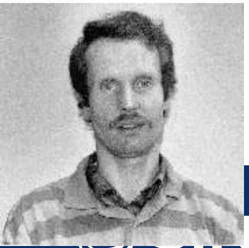

S. W. Løvseth

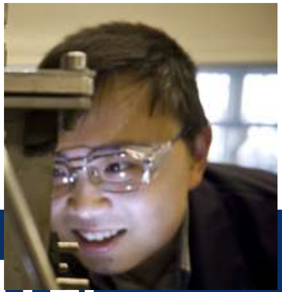

T. Gundersen


J. Pettersen


B. Müller


M. Hammer


K. Kolsaker


He Zhao


C. Dorao


P. K. Aursand


M. J. Mølnvik

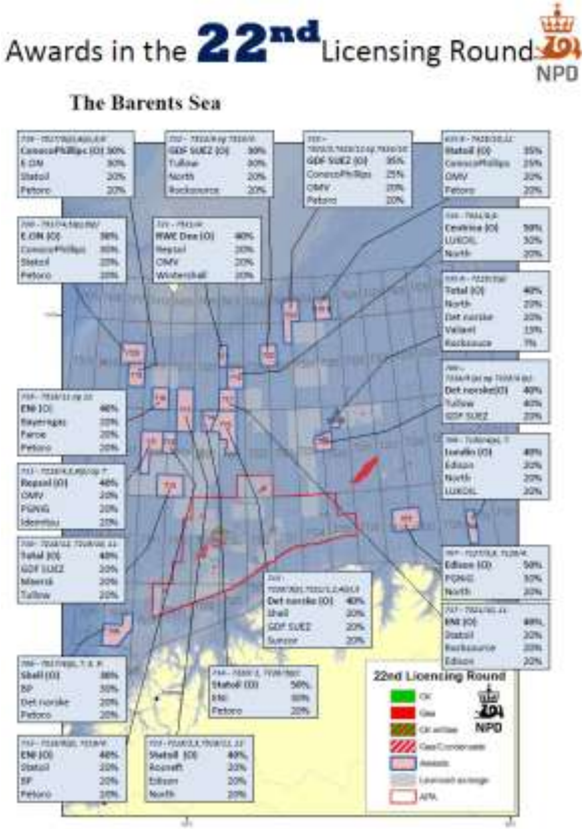

J. Lowengrub

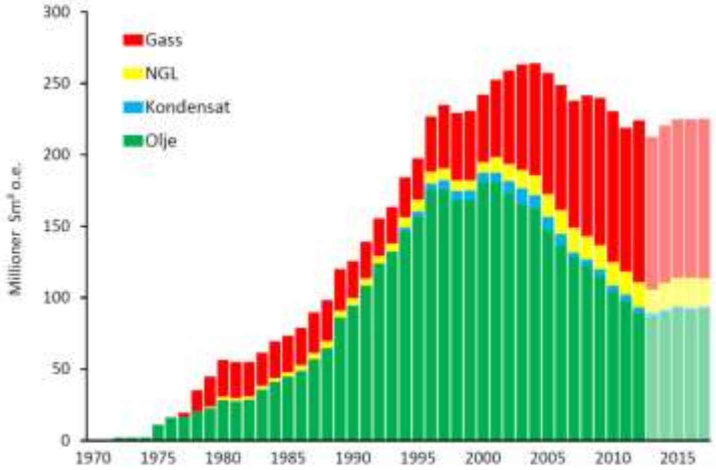

N. E. haugen

No picture:
H. T. Walnum

Motivation for research on LNG liquefaction

- Global trends
  - LNG penetration in the energy market has increased tremendously during last decades
  - Rapid LNG growth will continue
    - Increased demand according to IEA's 2 DS
    - Large regional variation in LNG price
    - High number of LNG carriers under order
- National trends
  - Higher NG than oil production in terms of o.e.
  - Remote fields / associated gas
- LNG plants are expensive to construct and operate
  - Cost reductions and improved realibility have big impact!





Enabling Low-Emission LNG Systems


Melkøya september 2008 Photo: Eiliv Leren - Statoil

Fundamentals for multilevel modelling

- Competence building project (KMB -> KPN) with co-funding from the Research Council of Norway (PETROMAKS Programme)
- SINTEF and NTNU are research partners
- GDF SUEZ and Statoil are industrial partners
- Project duration:
  - 6 years (2009-2014)
  - Start-up Q3 2009

http://www.sintef.no/lelng

Low-Emission LNG Systems
Project Goal

Facilitate sustainable production of natural gas by developing

- **knowledge**
- **competence**
- **tools**

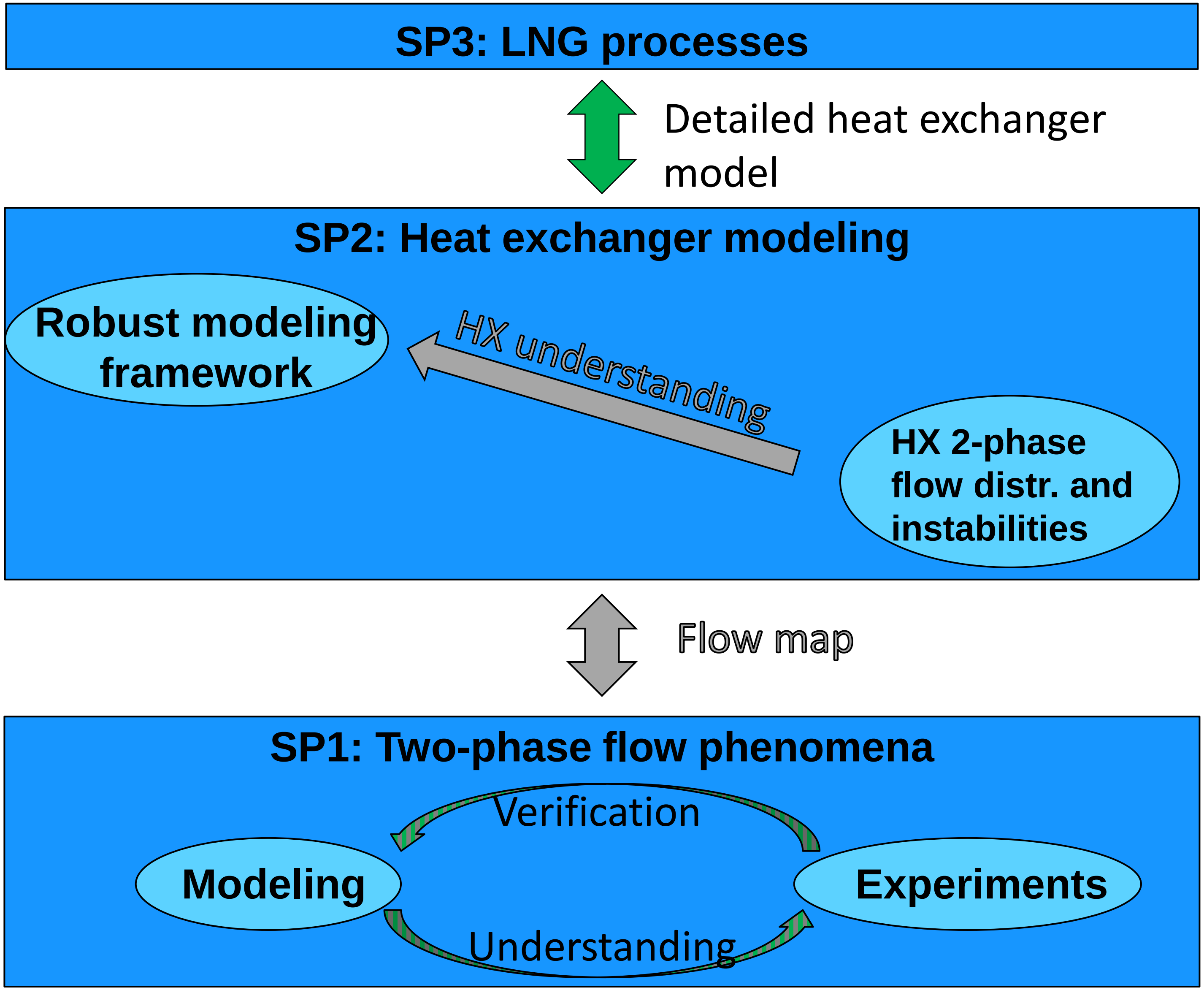
enabling

- evaluation
- design
- operation

of innovative, environmentally safe, cost-effective, and energy-efficient LNG systems.

CEO Arvid Hallén, Research Council of Norway
Opening PETROMAKS Status Conference 2012-10-24

Low-Emission LNG Overview



SP3: LNG processes

Detailed heat exchanger model

SP2: Heat exchanger modeling

Robust modeling framework

HX understanding

HX 2-phase flow distr. and instabilities

Flow map

SP1: Two-phase flow phenomena

Modeling

Verification

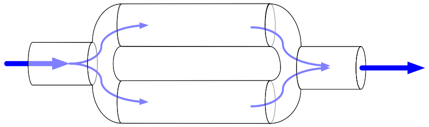
Understanding

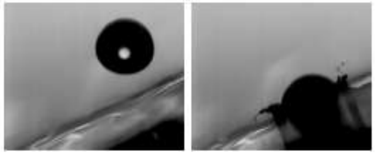
Experiments

Scale

Photo: The Linde group

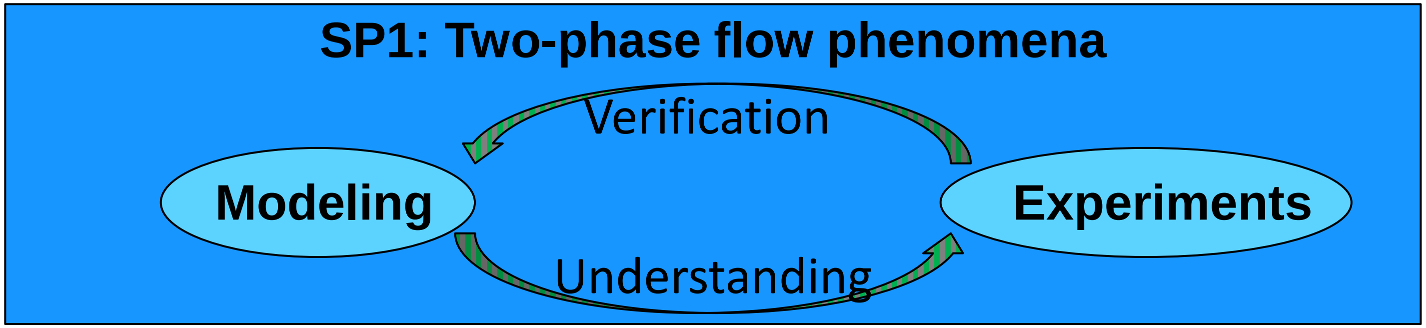
Photo: The Linde group





Low-Emission LNG Overview

Scale



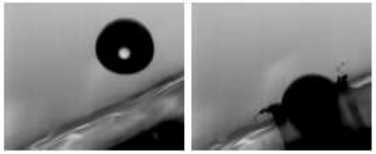
SP1: Two-phase flow phenomena

Modeling

Verification

Understanding

Experiments



Motivation: Two-phase flow phenomena

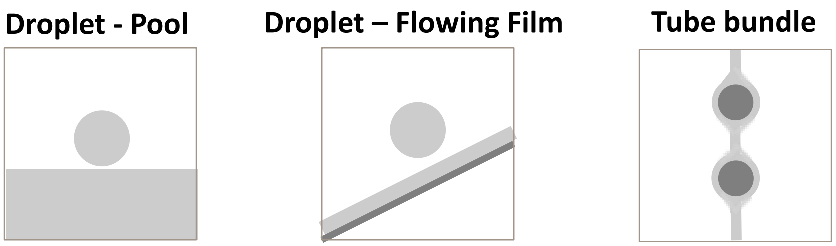
Purpose of work package

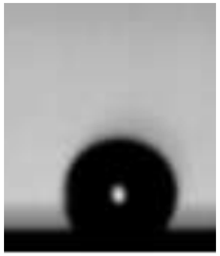
To gain insight into fundamental phenomena occurring in heat exchangers in liquefaction plants.

Basic hypothesis

A thorough understanding of the processes and phenomena occurring at a small-scale level in the heat exchanger is necessary to obtain an improved understanding of the heat exchanger, its design and operation.

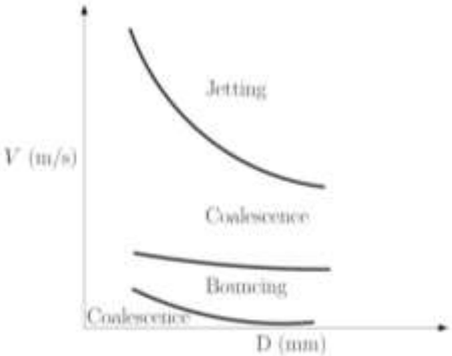
Enabling low-emission LNG systems
SP1: Two-phase flow phenomena in LNG processes



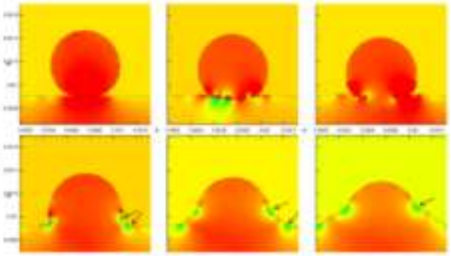


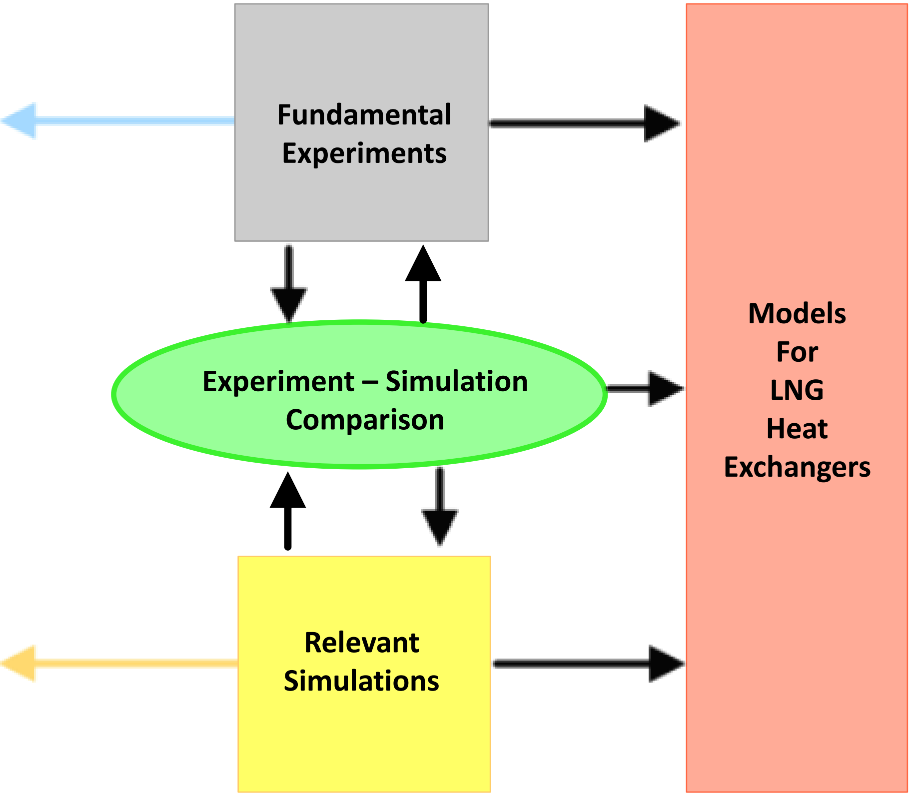
Shear flow

Droplet-column flow



Example : water droplets on water pool





Fundamental Experiments

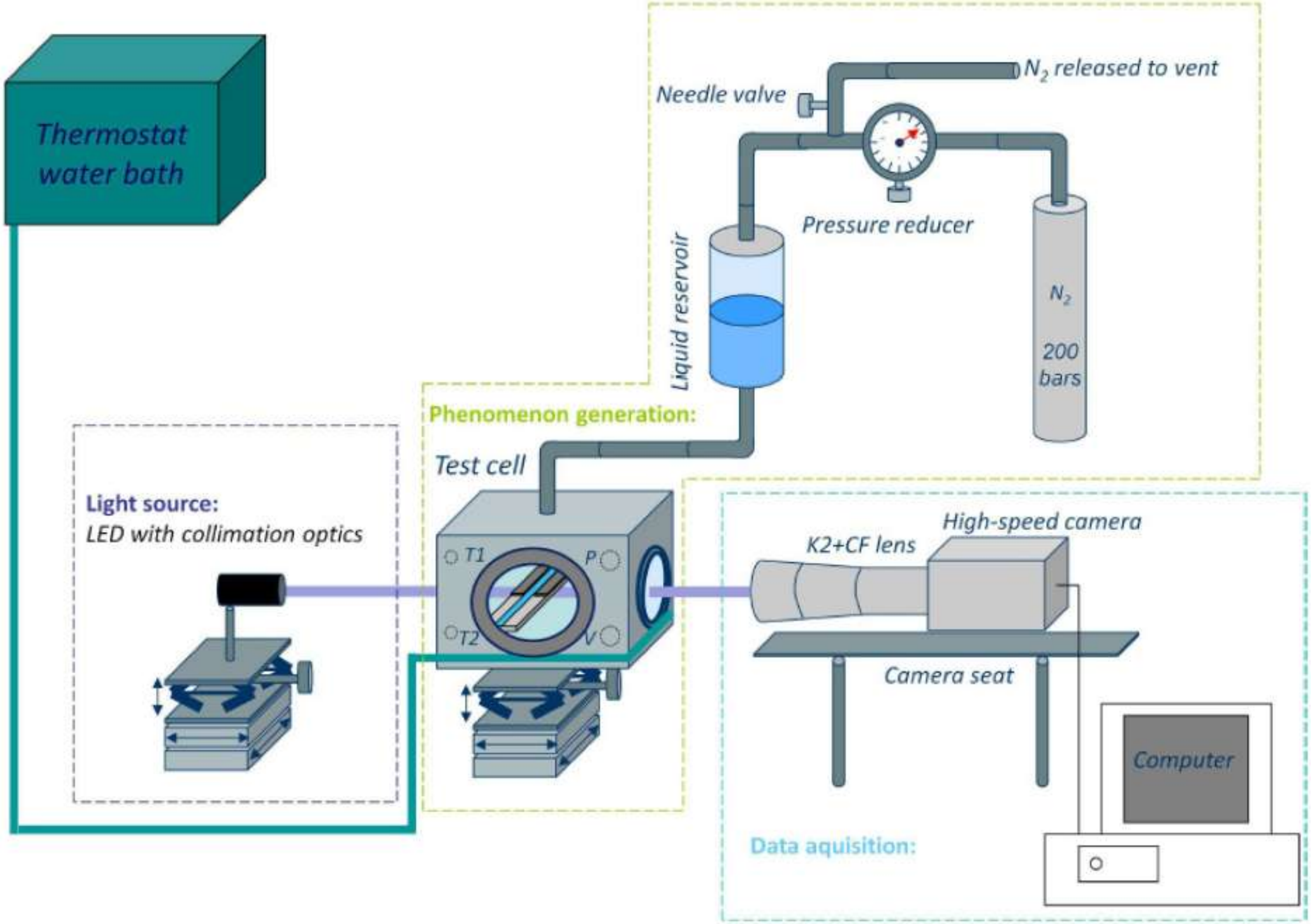
Experiment – Simulation Comparison

Relevant Simulations

Models For LNG Heat Exchangers

Experimental Study of detailed flow phenomena

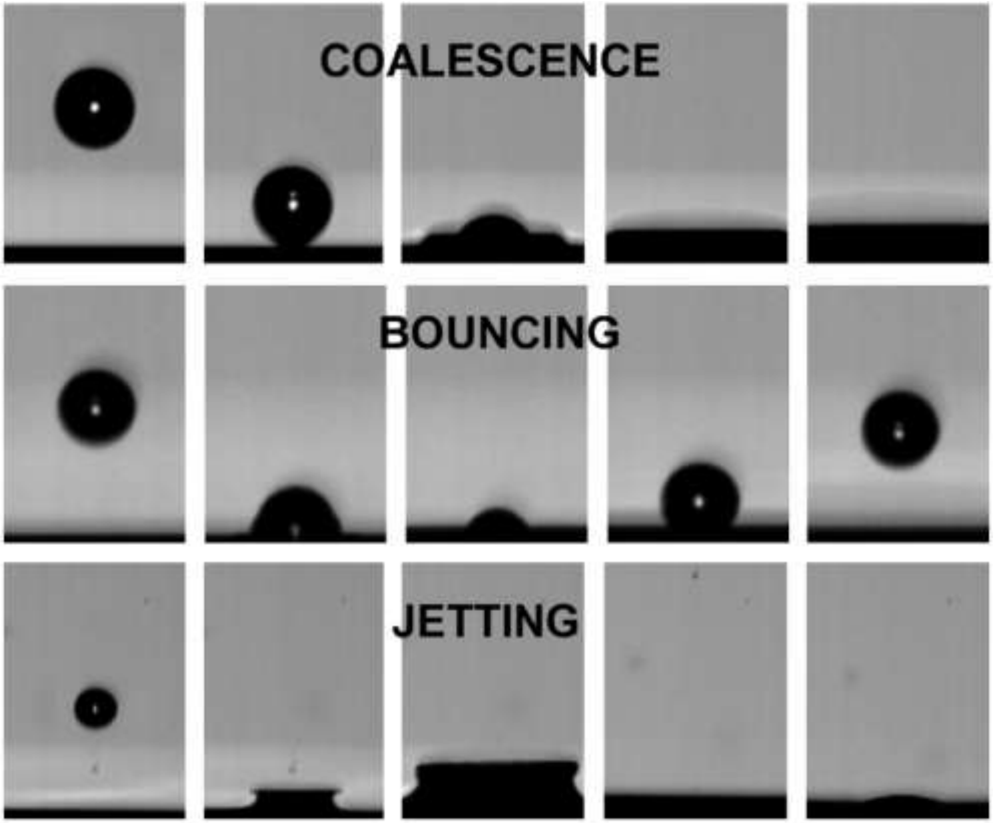
Detailed experiments necessary in order to learn the droplet / film behaviour and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.



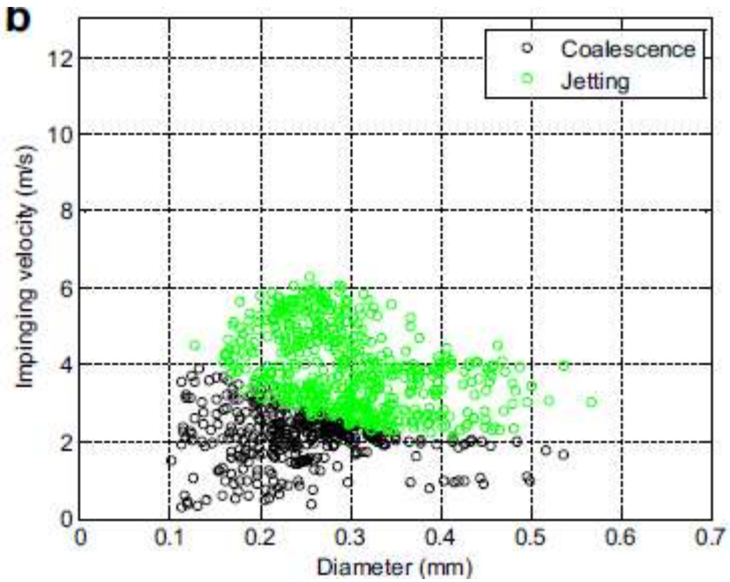
Experimental study of detailed flow phenomena

Detailed experiments necessary in order to learn the droplet / film behavior and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.

- Droplet falling in deep pool



H. Zhao et al. / Journal of Natural Gas Science and Engineering 2 (2010) 259–269

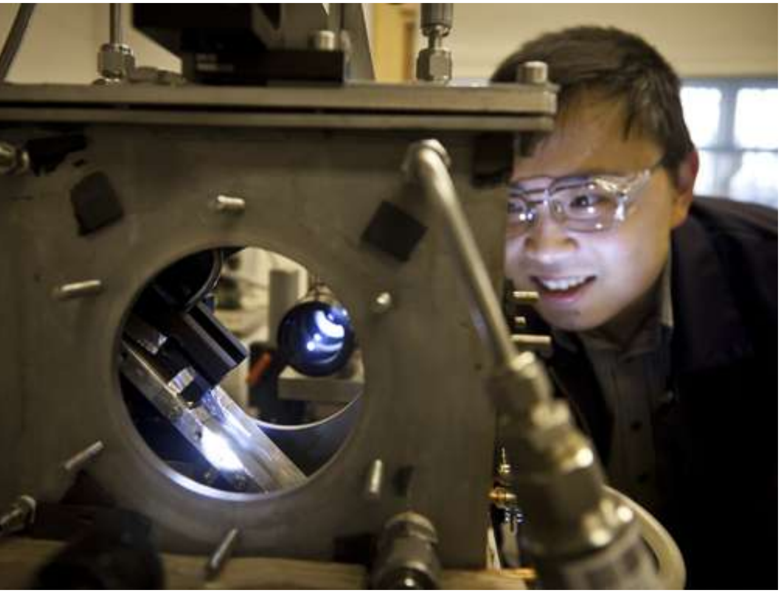


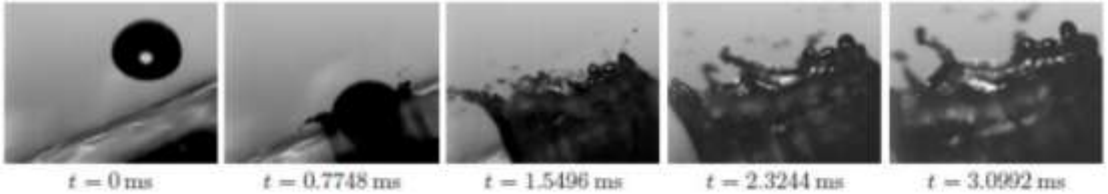
Experimental study of detailed flow phenomena

Detailed experiments necessary in order to learn the droplet / film behavior and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.

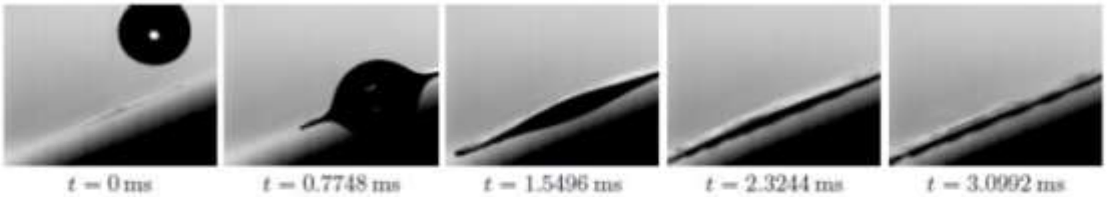
- Droplets falling
  - in deep pool
  - on films flowing on tilted board

Brunsvold, A., Å. Ervik, and H. Zhao, ASME 2013 Fluids Engineering Division Summer Meeting. 2013, ASME. p. V01CT17A003





(b) n-pentane film $\Delta = 0.25\,\mathrm{mm}$, $\mathrm{Re}_f = 1241$

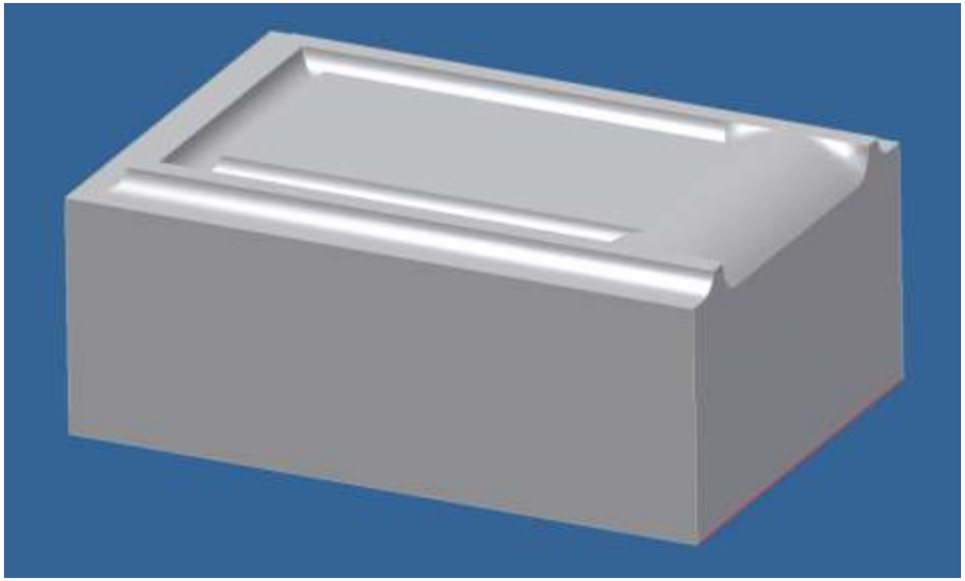


(c) n-pentane on dry board

Experimental study of detailed flow phenomena

Detailed experiments necessary in order to learn the droplet / film behavior and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.

- Droplets falling
  - in deep pool
  - on films flowing on tilted board
  - films of different thickness

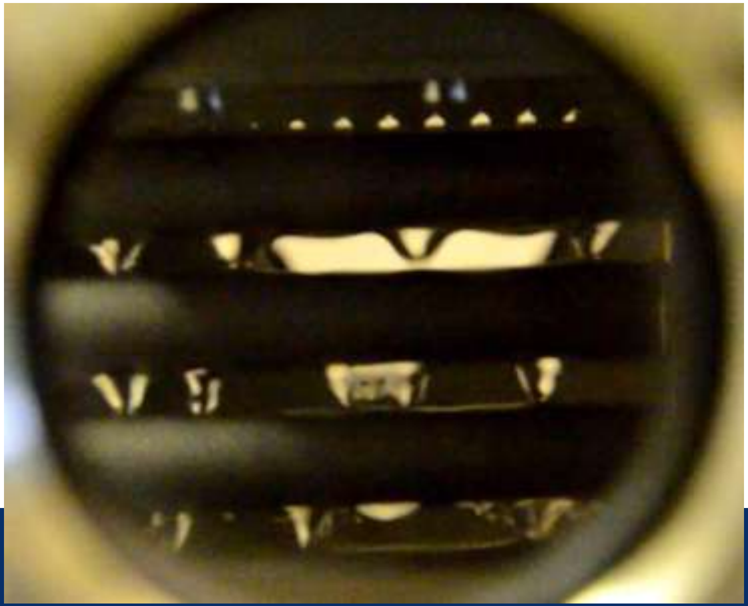


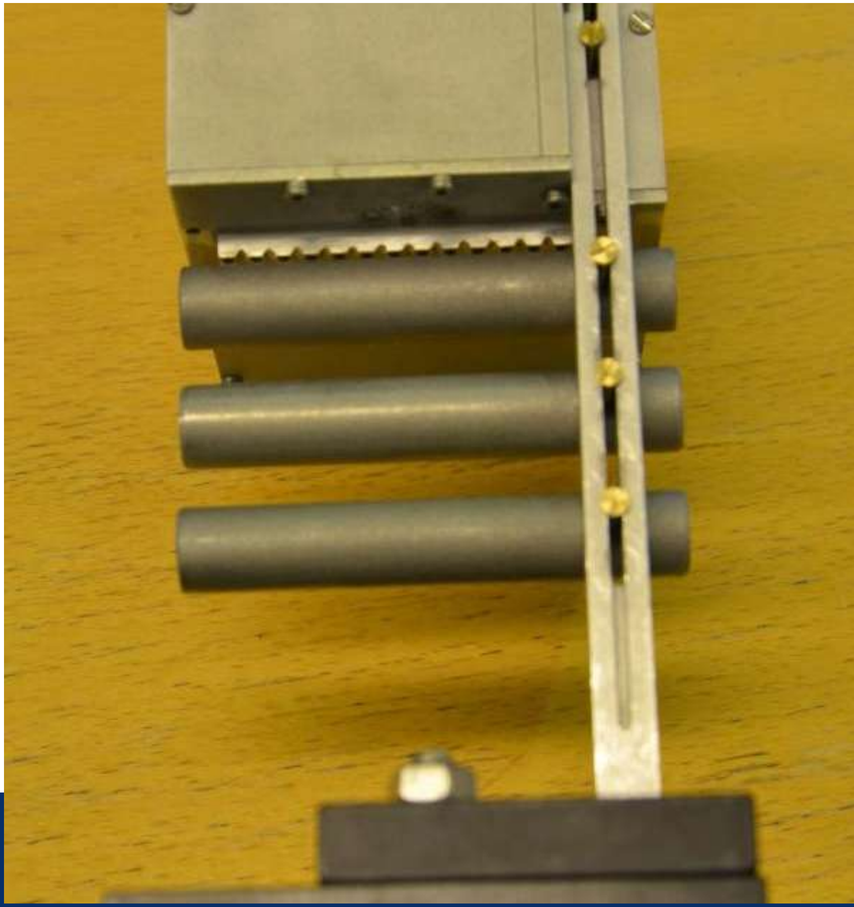
Experimental study of detailed flow phenomena

A. Austegard
TGTC-3
Session A2

Detailed experiments necessary in order to learn the droplet / film behavior and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.

- Droplets falling
  - in deep pool
  - on films flowing on tilted board
  - films of different thickness
- Study of different regimes of flow falling on cylinders



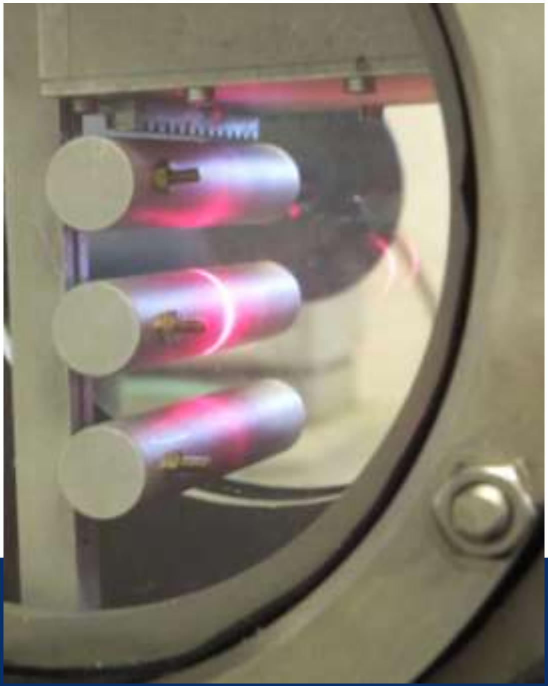


Experimental study of detailed flow phenomena

Detailed experiments necessary in order to learn the droplet / film behavior and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.

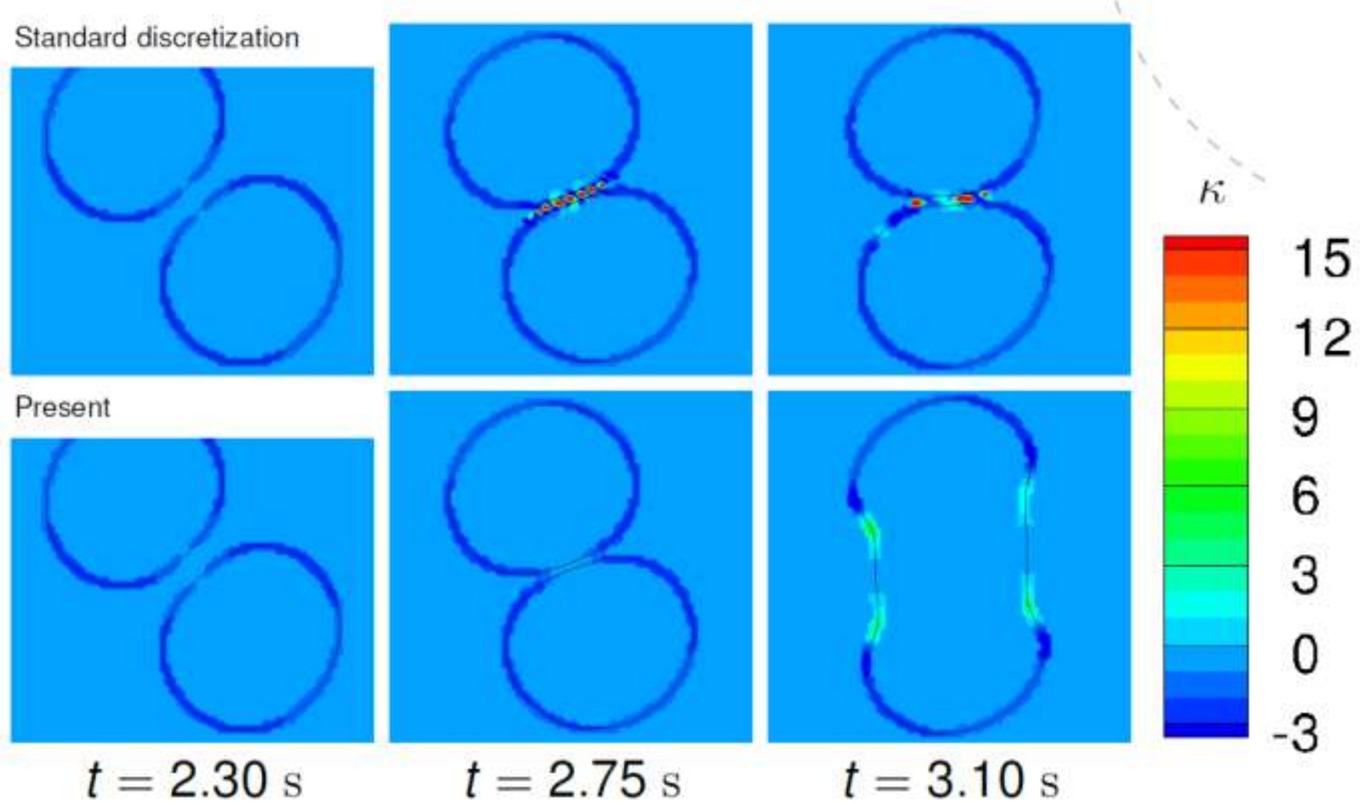
- Droplets falling
  - in deep pool
  - on films flowing on tilted board
  - films of different thickness
- Study of different regimes of flow falling on cylinders
- Film thickness measurements

(In progress)



Modeling of detailed flow phenomena

- Based on level-set method to track interfaces
- Reformulation needed in order to account for discontinous curvature

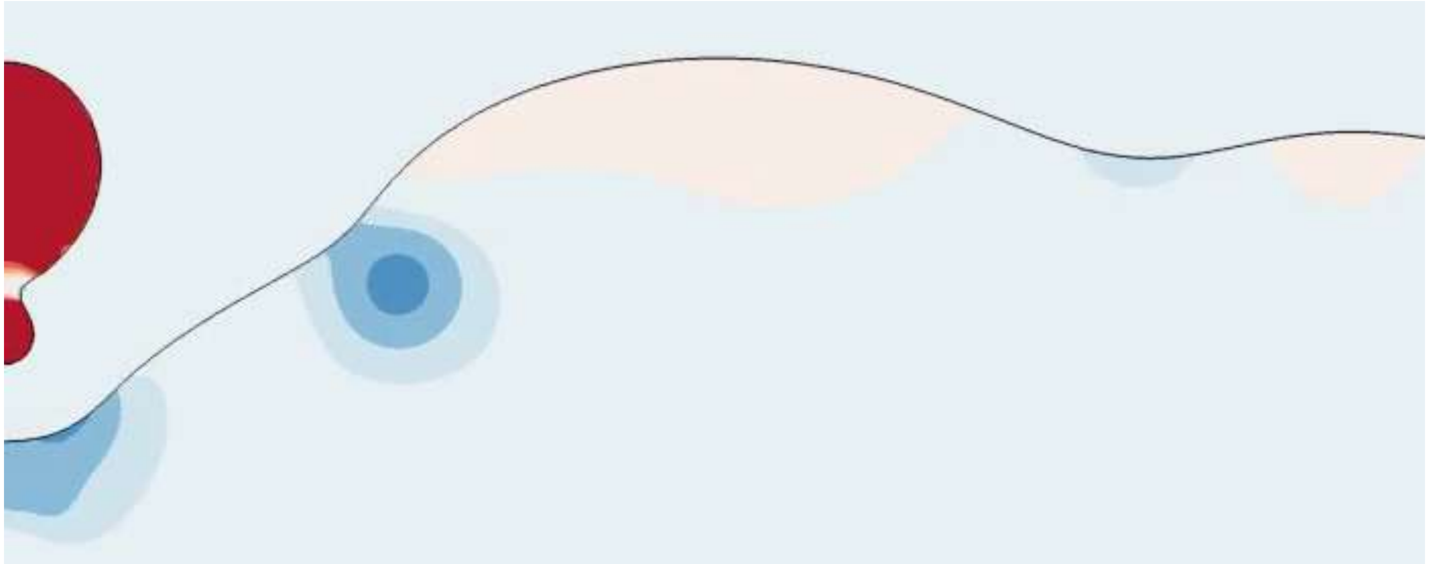


Lervåg, K.Y. and Å. Ervik, Curvature calculations for the level-set method, in Numerical Mathematics and Advanced Applications 2011. 2013, Springer. p. 209-217

Karl Yngve Lervåg, PhD, Sept 2013

Modeling of detailed flow phenomena

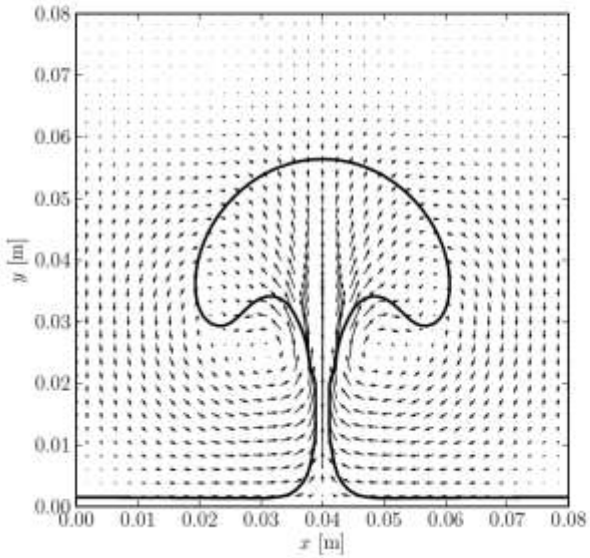
- Based on level-set method to track interfaces
- Reformulation needed in order to account for discontinous curvature
- Model-experiment comparison for droplet-film coalescence possible



Modeling of detailed flow phenomena

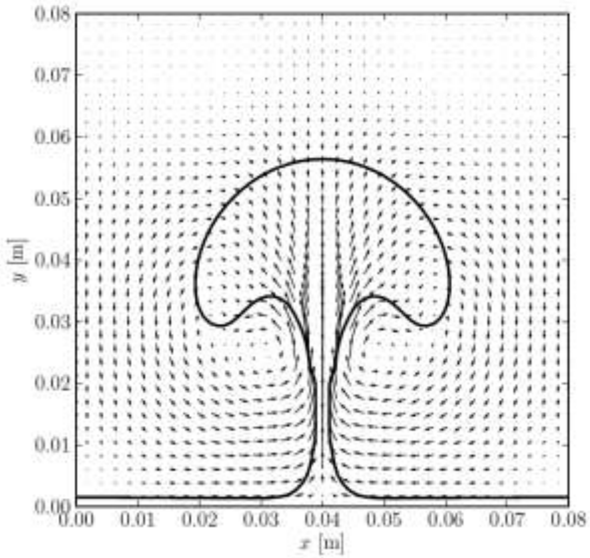
- Based on level-set method to track interfaces
- Reformulation needed in order to account for discontinous curvature
- Describes droplet-film coalescence
- Heat and mass transfer

M. Aa.
Gjennestad
TGTC-3
Session A1



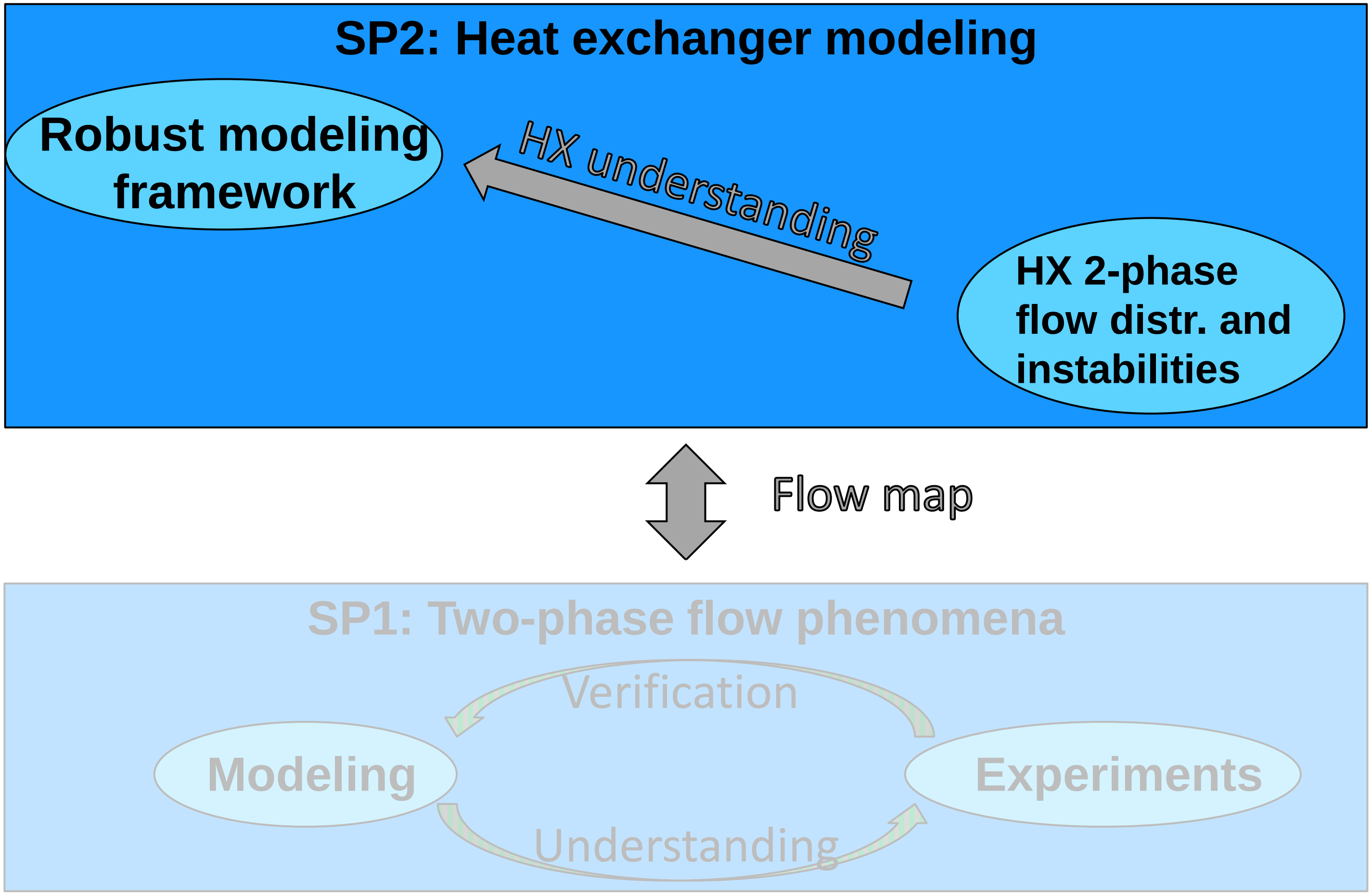
Modeling of detailed flow phenomena

- Based on level-set method to track interfaces
- Reformulation needed in order to account for discontinous curvature
- Describes droplet-film coalescence
- Heat and mass transfer
  - Including heat transfer and condensation in pipes (in progress)



Low-Emission LNG Overview

Scale



SP2: Heat exchanger modeling

Robust modeling framework

HX understanding

HX 2-phase flow distr. and instabilities

Flow map

SP1: Two-phase flow phenomena

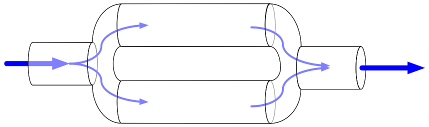
Verification

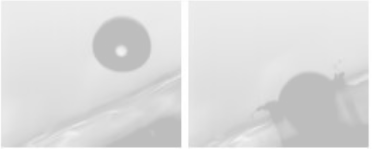
Modeling

Experiments

Understanding

Photo: The Linde group

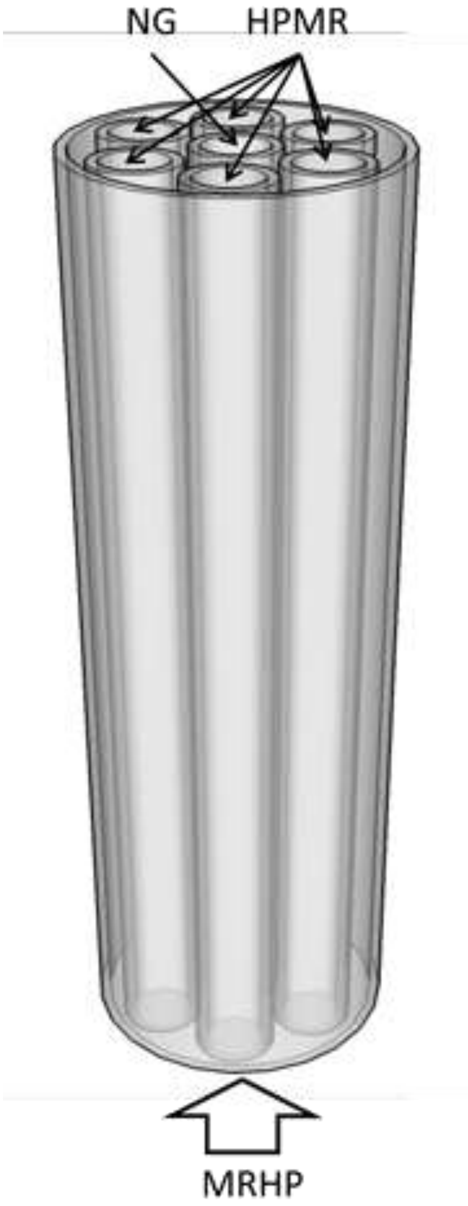




Heat Exchanger Modeling

FLEXHx: A Flexible Heat Exchanger Network

- Normally/ elsewhere, heat exchangers are simplified:
  - composite curve based
  - constant
    - heat transfer rates
    - heat capacities
  - constant or simplified pressure drop model.
- Geometry information is important in order to model:
  - Non-idealities
  - Dynamic behavior
  - **Realistic weight / volume => costs**



Heat Exchanger Modeling

FLEXHx: A Flexible Heat Exchanger Network

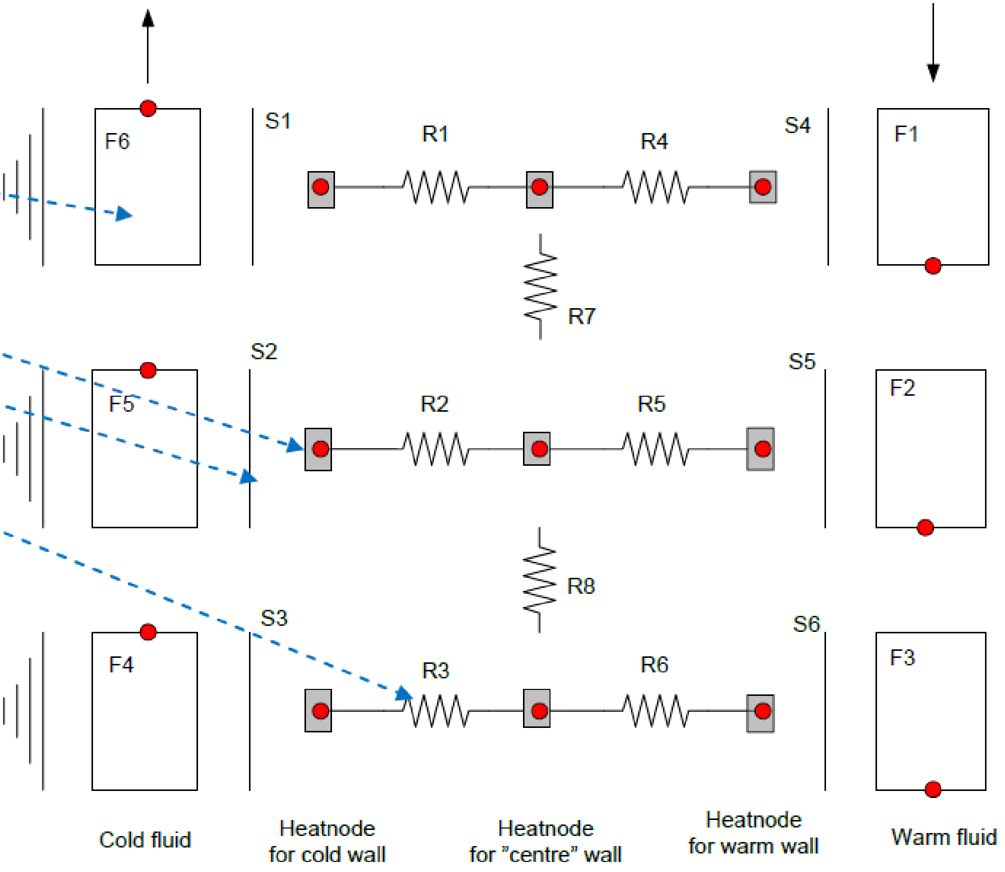
Generic tool with building blocks of:

- fluid nodes
- heat nodes
- surfaces
- thermal resistors

- splitters
- mixers
- flash units
- flow restrictions

Flexible and robust data structure to handle various heat exchanger variants

Counter-flow HX with wall heat conduction



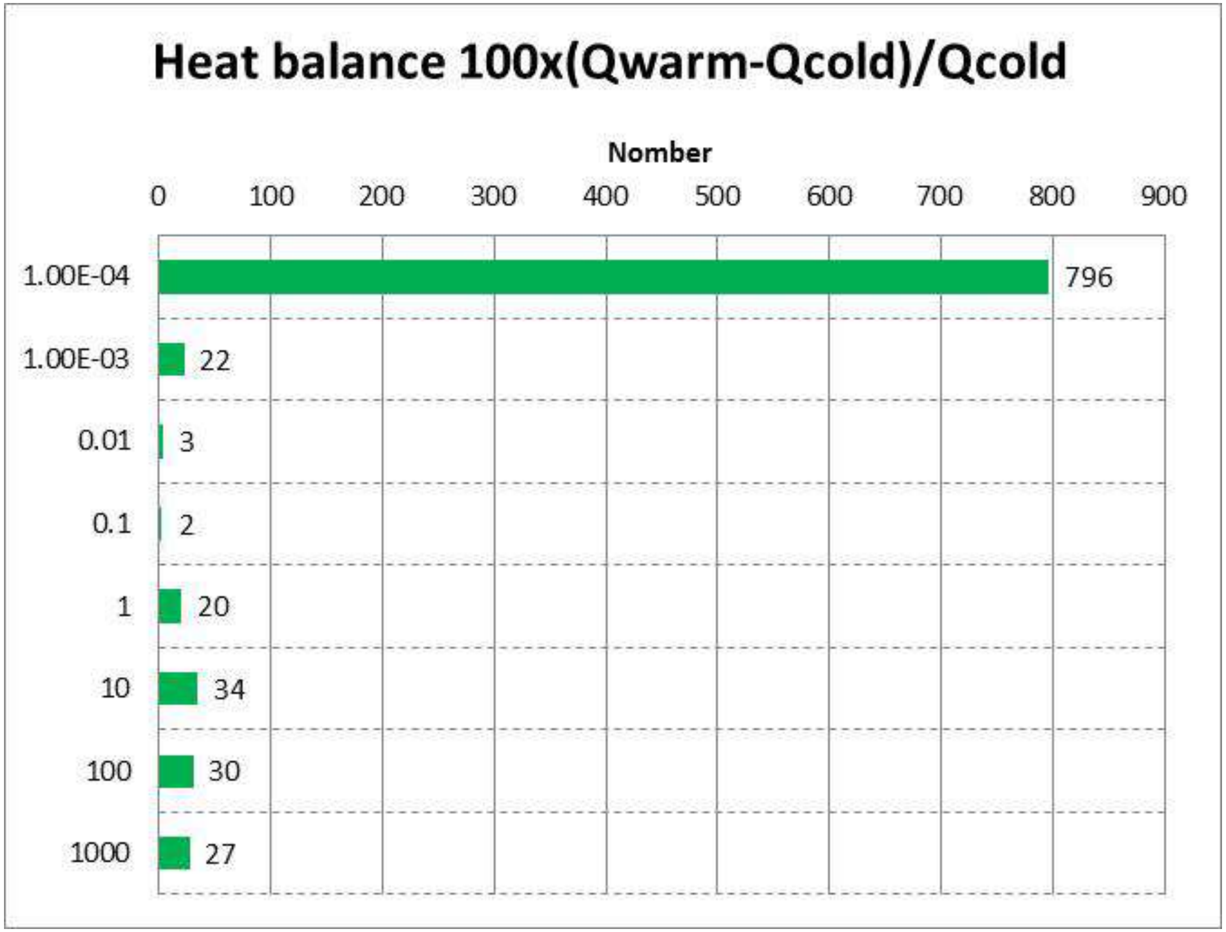
Axial and radial conduction

- Currently implemented: Shell & tube, plate-fin

Skaugen, G., et al., A flexible and robust modelling framework for multi-stream heat exchangers. Computers and Chemical Engineering, 2013. 49(11): p. 95-104

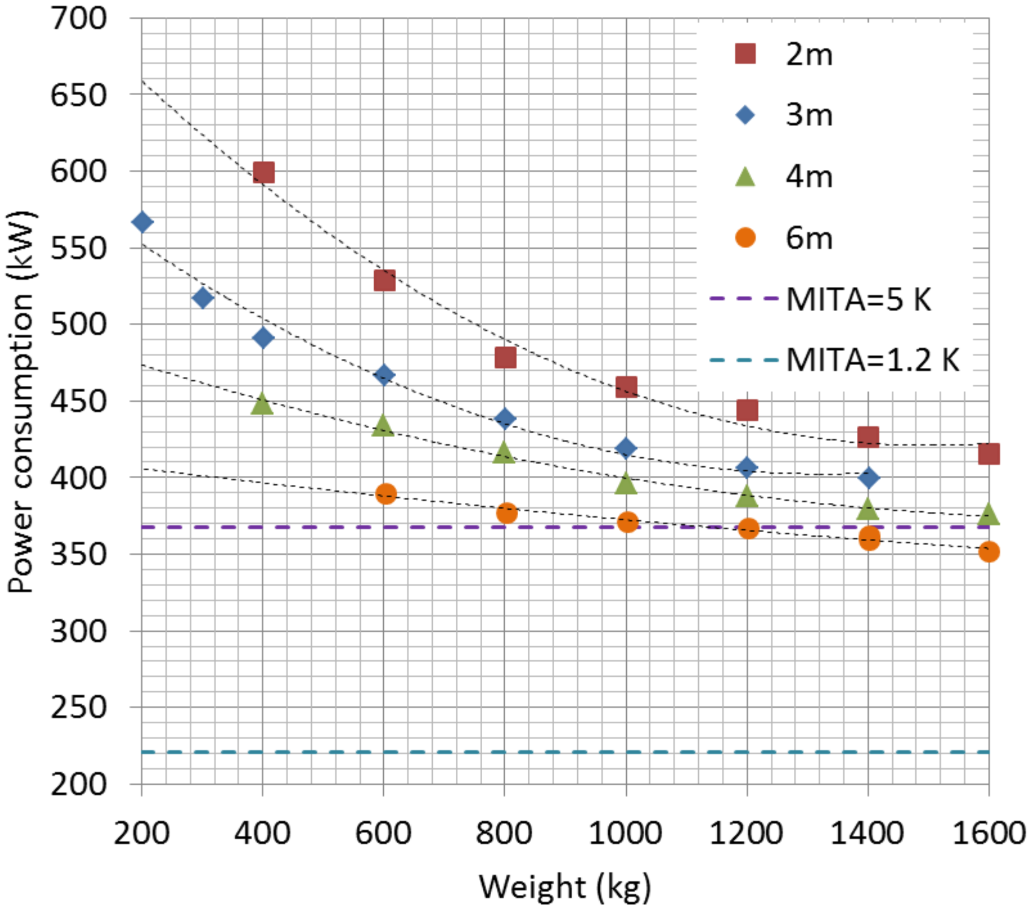
Heat Exchanger Modeling

FLEXHx: A Flexible Heat Exchanger Network - Robustness



Heat Exchanger Modeling

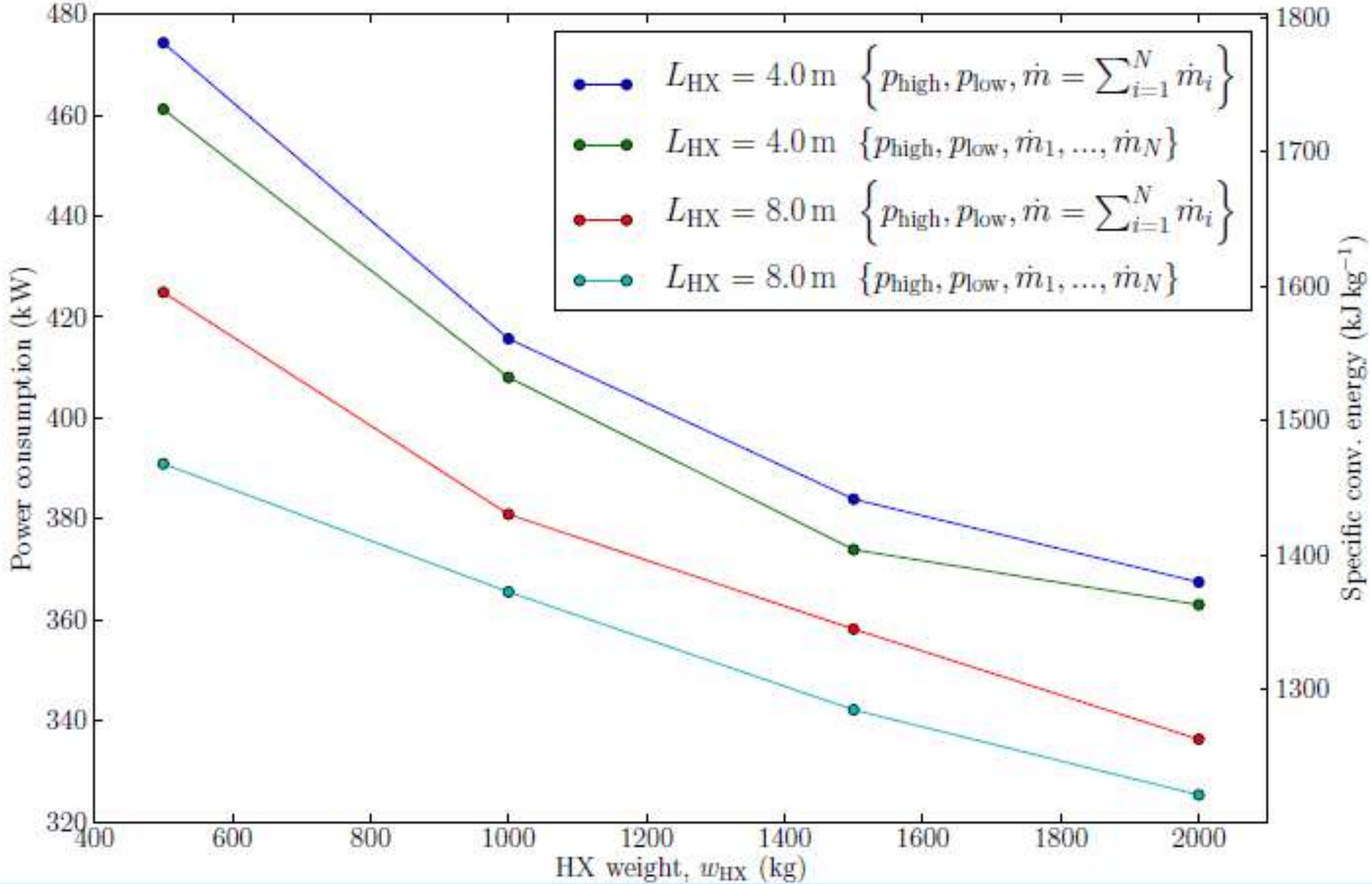
FLEXHx: A Flexible Heat Exchanger Network: Optimization of a simple single cycle LNG process with no refrigerant optimization



G. Skaugen et al., ICAE2013

Heat Exchanger Modeling

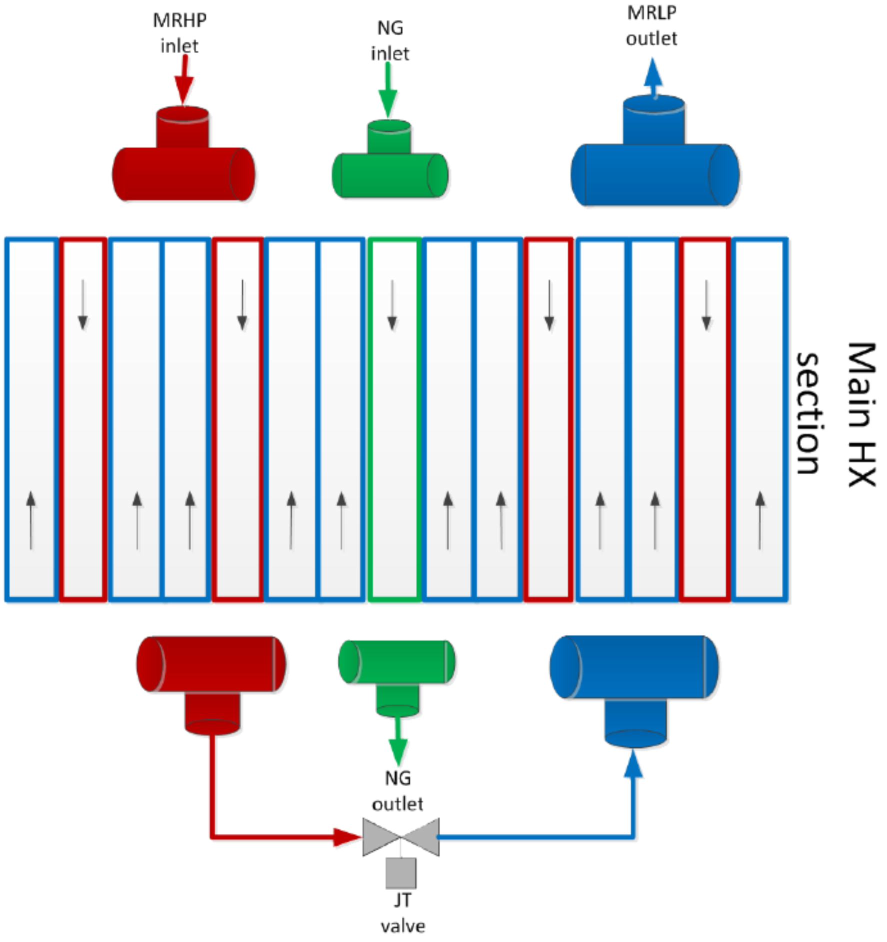
FLEXHx: A Flexible Heat Exchanger Network: Optimization of a simple single cycle LNG process with refrigerant optimization – work under progress



Heat Exchanger Modeling

FLEXHx: A Flexible Heat Exchanger Network: Instabilities

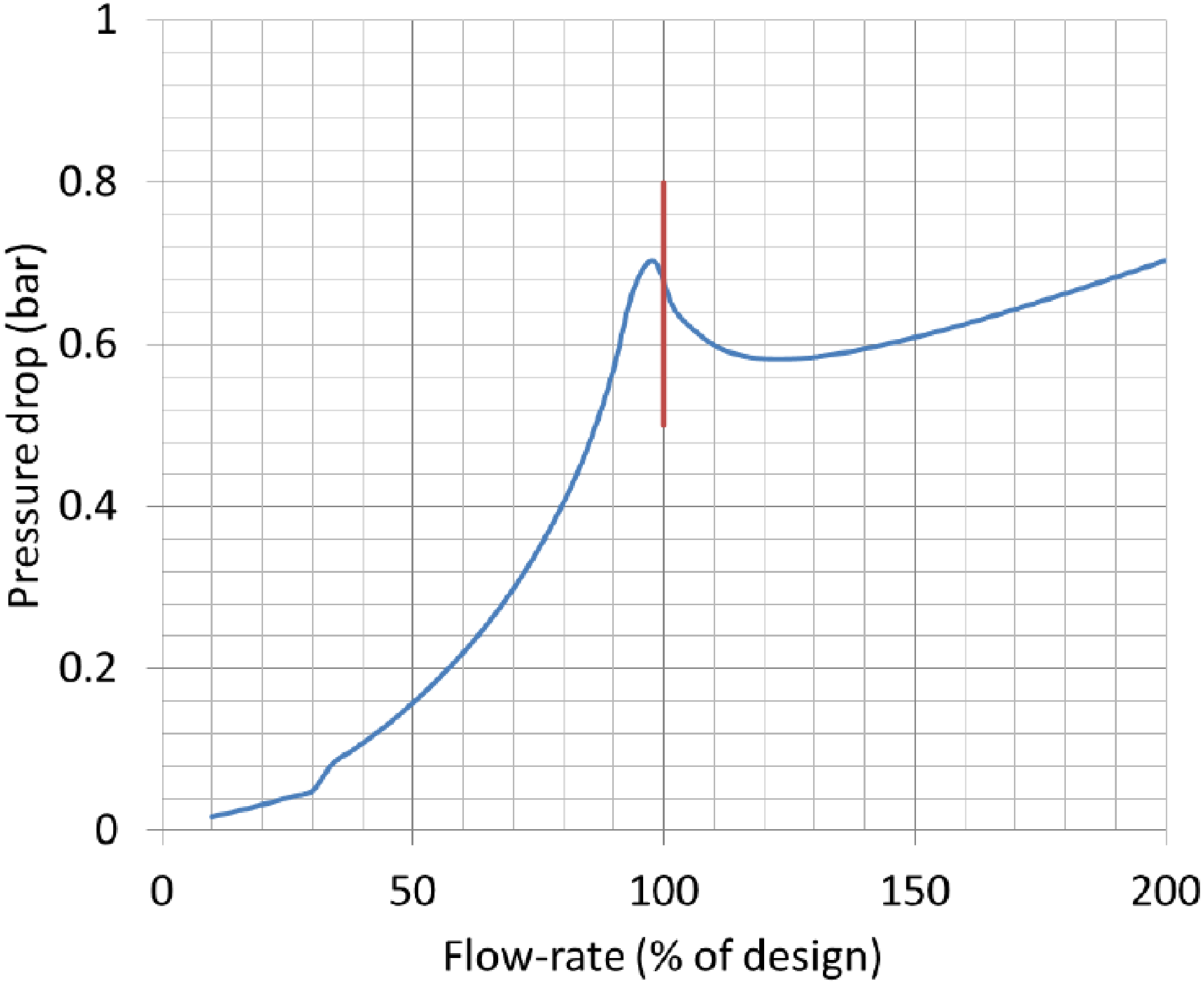
- Looking at local effects: Individual layers



Heat Exchanger Modeling

FLEXHx: A Flexible Heat Exchanger Network: Instabilities

- Ledinegg: Caused by increased vapor void fraction while boiling



Heat Exchanger Modeling

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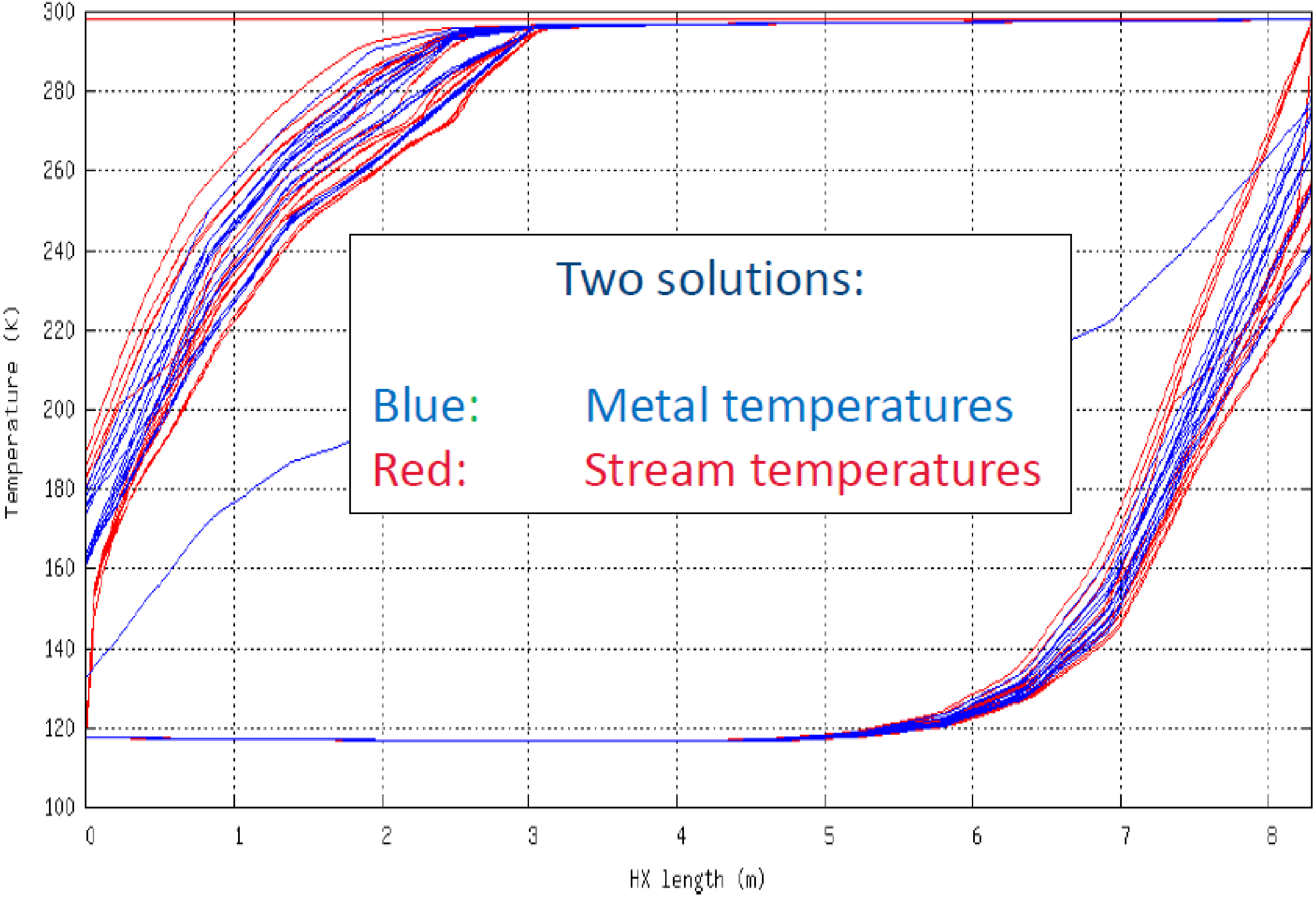


Two solutions:

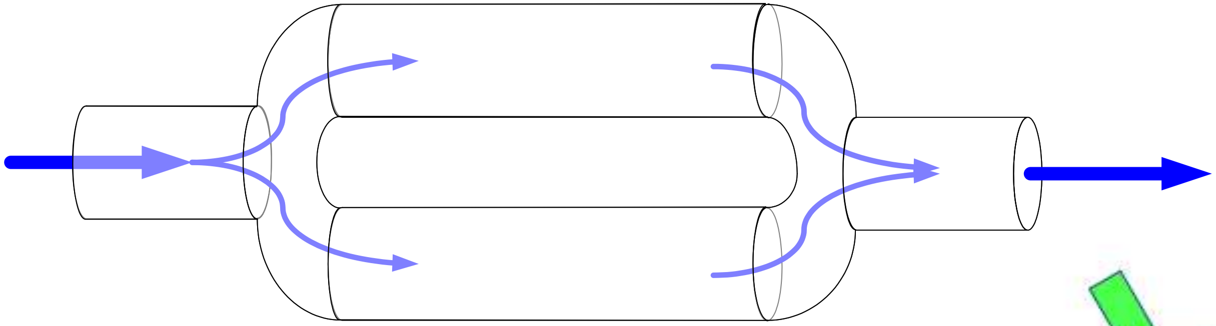
Blue: Metal temperatures
Red: Stream temperatures

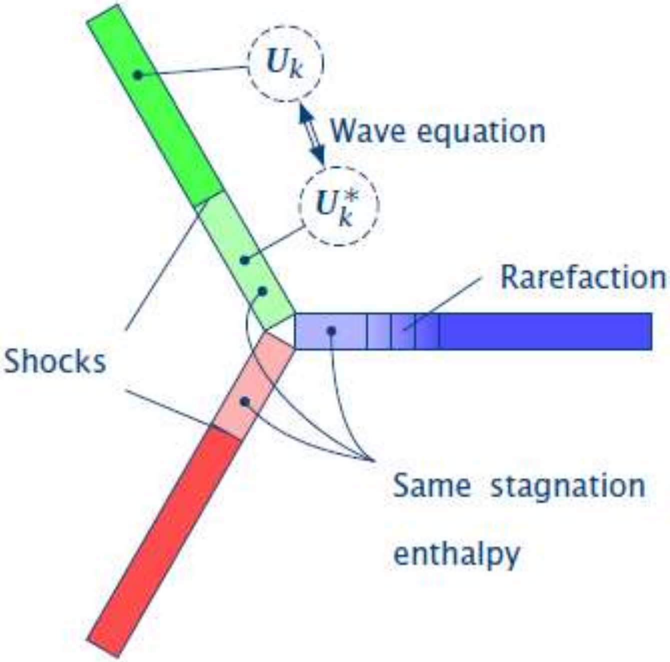
G. Skaugen
TGTC3
Session A5

Heat Exchanger Modeling

Junction flow modeling : Looking at dynamic effects

A Morin
TGTC3
Session A2





Gunhild Allard Reigstad: Mathematical Modelling of Fluid Flows in Pipe Networks, PhD, April 2014

Low-Emission LNG Overview

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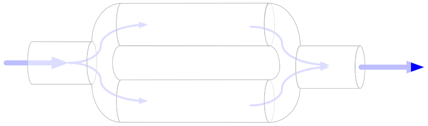
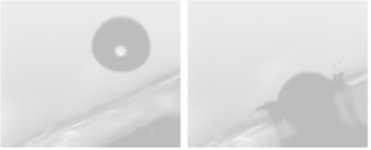
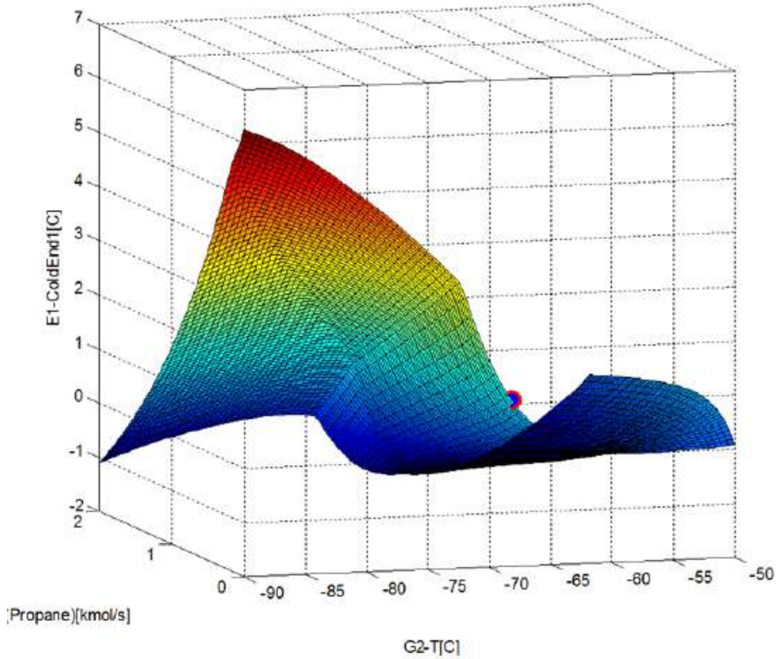
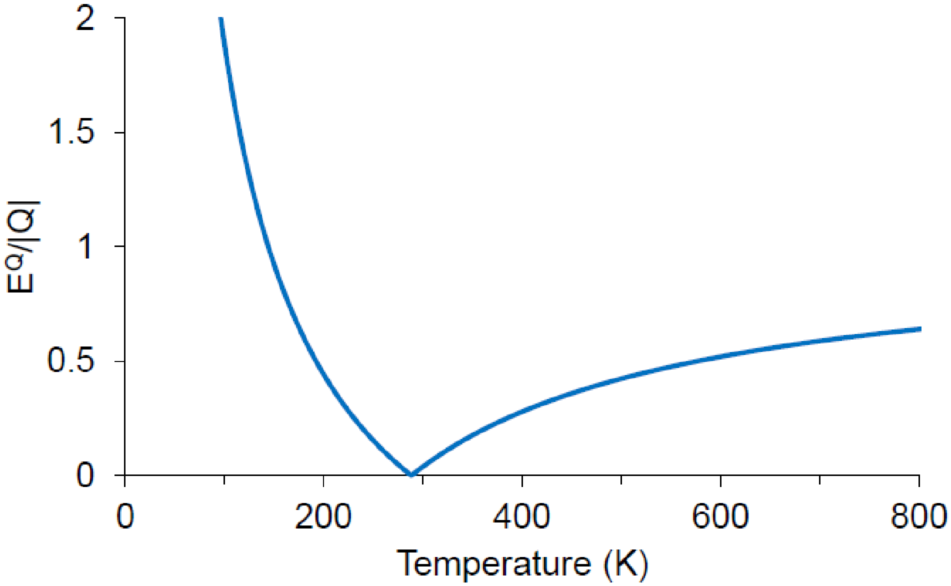




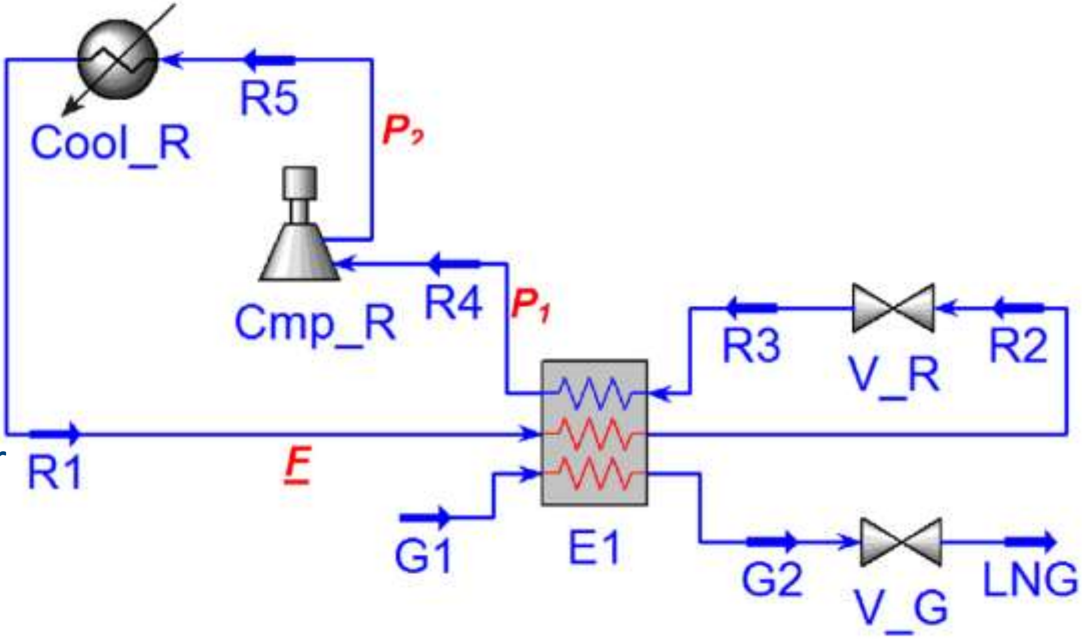
LNG Process optimization

- LNG liquefaction is energy expensive
- ….but difficult to optimize
  - At least 3+N-1 dimensions
    - N number of components in refrigerant
  - Non-convex
  - Non-linear constraints
  - Kinks in derivatives
  - Non analytical objective function
- Also difficult to find solution manually, especially for complex processes





LNG Process optimization



Main approach

- Use a modularized tool based on:
  - Commercial flow-sheet simulator
  - Gradient based optimization
    - Sequential quadratic programming (SQP)
- Not trivial to implement
- For simple cases shown to be more efficient than some other published work
- Typical optimization time for a PRICO process ~5 minutes

Wahl, P.E., S.W. Løvseth, and M.J. Mølnvik, Optimization of a simple LNG process using sequential quadratic programming. Computers and Chemical Engineering, 2013. 56: p. 27-36.

LNG Process optimization

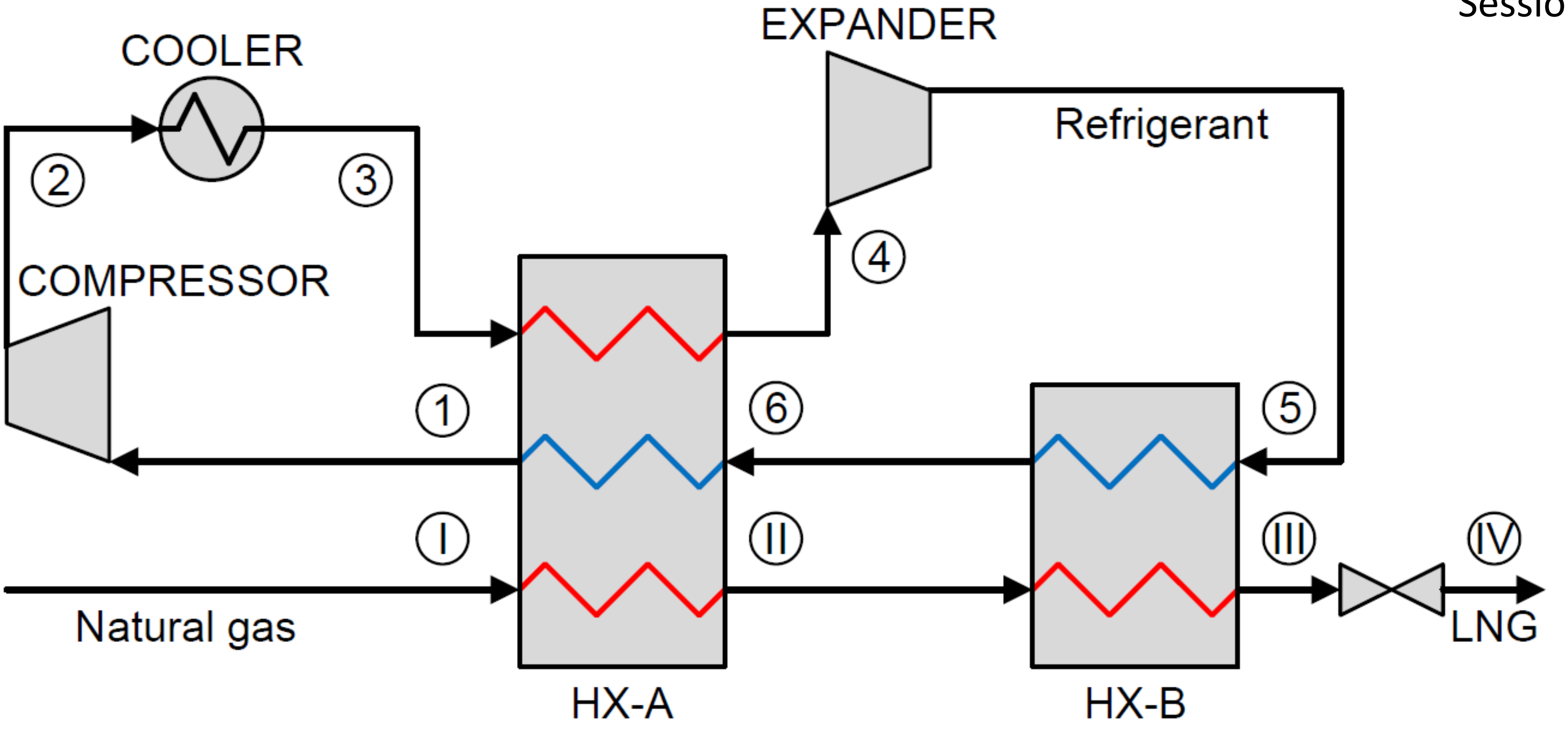
- Optimization module in tool can easily be substituted with other routines
- Results shown for **single cycle process** – trend clearer with more complex processes
- Gradient based require far fewer evaluations
- Currently working on complex processes (up to 3 cycles) with some success

	50 %	25 %	10 %	5 %	2 %	1 %	0.1 %	0.01 %
NLPQLP	100	100	100	100	100	99	99	99
fmincon								
-SQP	100	100	100	100	100	100	98	98
-Interior-point	100	100	100	100	92	88	84	81
-Active set	100	100	100	99	98	98	95	89
LGO								
-Local search only	100	80	60	60	30	30	20	20
-Branch and Bound	100	100	90	80	60	50	40	40
-Global Adaptive Random Search	100	100	100	90	60	50	40	40
-Multi-start Search	100	100	100	100	100	100	100	100
Modified ECJ	100	100	100	100	100	100	30	0
ASA	100	100	100	100	70	30	0	0
GLOBAL (Fortran)								
-unirandi	100	60	10	0	0	0	0	0
-quasi Newton	100	100	100	100	100	80	0	0
GLOBAL (MATLAB)								
-BFGS	100	100	100	70	30	20	0	0
-unirandi	100	100	100	100	50	0	0	0
SNOBFIT	100	100	90	70	10	0	0	0
MCS	100	50	0	0	0	0	0	0

LNG Process optimization:

B. Austbø
TGTC3
Session A4

- PhD work focusing on impact of formulation of problem and thermodynamics
- At TGTC3: Single expander process optimization with different thermodynamics



Enabling Low-Emission LNG Systems

CEO Arvid Hallén, Research Council of Norway
Opening PETROMAKS Status Conference 2012-10-24

Journal and proceedings publications from Low-Emission LNG

Accepted / Published

1. Skaugen, G., et al., Use of sophisticated heat exchanger simulation models for investigation of possible design and operational pitfalls in LNG processes. Journal of Natural Gas Science and Engineering, 2010. 2(5): p. 236-243.
2. Lervåg, K.Y., Calculation of interface curvature with the level-set method, in MekIT'11: Sixth National Conference on Computational Mechanics, Trondheim 23-24 May 2011. 2011, Tapir Akademisk Forlag. p. 171-187.
3. Zhao, H., A. Brunsvold, and S.T. Munkejord, Transition between coalescence and bouncing of droplets on a deep liquid pool. International Journal of Multiphase Flow, 2011. 37(9): p. 1109-1119.
4. Zhao, H., S.T. Munkejord, and A. Brunsvold, Investigation of droplets impinging on a deep pool: transition from coalescence to jetting. Experiments in Fluids, 2011. 50(3): p. 621-635.
5. Zhao, H., et al., Droplet impact on a flowing liquid film, in PROCEEDINGS OF THE DIPSI WORKSHOP 2011 - Droplet Impact Phenomena & Spray Investigations. 2011, Università degli Studi di Bergamo: BERGAMO, ITALY. p. 73-80.
6. Reigstad, G.A. and T. Flåtten, An Improved Roe solver for the drift-flux two-phase flow model, in Proceedings of the 8th international conference on CFD in the oil & gas, metallurgical and process industries. 2012, SINTEF Materials and Chemistry. p. 366-374.
7. Austbø, B., P.E. Wahl, and T. Gundersen, Constraint handling in stochastic optimization algorithms for natural gas liquefaction processes, in 23 European Symposium on Computer Aided Process Engineering. 2013, Elsevier. p. 445-450.
8. Lervåg, K.Y. and Å. Ervik, Curvature calculations for the level-set method, in Numerical Mathematics and Advanced Applications 2011. 2013, Springer. p. 209-217.
9. Lervåg, K.Y., B. Müller, and S.T. Munkejord, Calculation of the interface curvature and normal vector with the level-set method. Computers & Fluids, 2013. 84(Sept): p. 218-230.
10. Skaugen, G., et al., A flexible and robust modelling framework for multi-stream heat exchangers. Computers and Chemical Engineering, 2013. 49(11): p. 95-104.
11. Wahl, P.E., S.W. Løvseth, and M.J. Mølnvik, Optimization of a simple LNG process using sequential quadratic programming. Computers and Chemical Engineering, 2013. 56: p. 27-36.
12. Brunsvold, A., Å. Ervik, and H. Zhao, Experimental methods for investigating the discrete droplet impact phenomena of a model fluid relevant for LNG heat exchangers, in ASME 2013 Fluids Engineering Division Summer Meeting. 2013, ASME. p. V01CT17A003.
13. Wilhelmsen, Ø., et al., Time efficient solution of phase equilibria in dynamic and distributed systems with DAE-solvers. Industrial & Engineering Chemistry Research, 2013. 52(5): p. 2130-2140.
14. Ervik, Å., K.Y. Lervåg, and S.T. Munkejord, A robust method for calculating interface curvature and normal vectors using an extracted local level set. Journal of Computational Physics, 2014. 257: p. 259-277.
15. Reigstad, G.A., NUMERICAL NETWORK MODELS AND ENTROPY PRINCIPLES FOR ISOTHERMAL JUNCTION FLOW. Networks and Heterogeneous Media, 2014. 9(1): p. 65-99.
16. Austbø, B. and T. Gundersen, Using Thermodynamic Insight in the Optimization of LNG Processes. Computer aided chemical engineering, 2014, accepted.

*) Shared acknowledgment with Remote Gas

Publications (more)

- 5 more scientific articles under peer-review
- **Two PhDs completed:**
  - Gunhild Allard Reigstad: *Mathematical Modelling of Fluid Flows in Pipe Networks*, April 2014
  - Karl Yngve Lervåg: *Calculation of interface curvatures with the level-set method for two-phase flow simulations and a second-order diffuse-domain method for elliptic problems in complex geometries*, September **2013**
- 22 conference publications held /accepted
- …of which 6 will be at TGTC3:
  - *Investigation of non-ideal behavior of plate-fin heat exchangers in LNG services using optimization techniques*
  - *The Enabling Low Emission LNG Systems Project*
  - *Flow pattern transitions and hysteresis effect in falling film flow over horizontal tubes*
  - *Modeling of heat transport in two-phase flow and of mass transfer between the phases using the level-set method*
  - *Pipe networks: coupling constants in a junction for isentropic Euler equations*
  - *OPTIMIZATION OF A SINGLE EXPANDER LNG PROCESS*

Conclusion

The Enabling Low-Emission LNG Systems project has provided

- knowledge
- competence
- tools

enabling

- evaluation
- design
- operation

of improved LNG Processes

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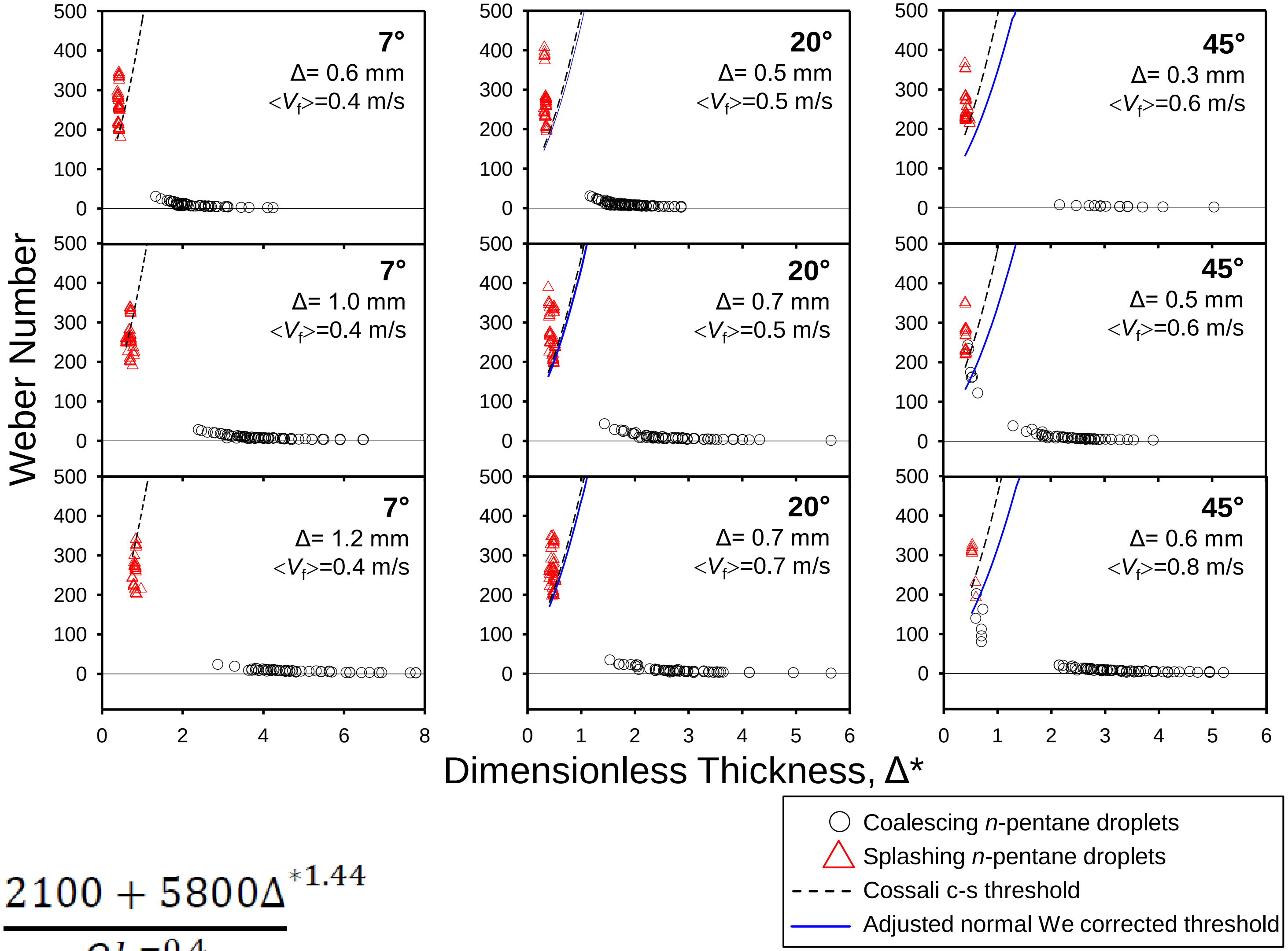
This work was financed through the Enabling Low-Emission LNG Systems project at SINTEF Energy Research, and the authors acknowledge the contributions of GDF SUEZ, Statoil and the PETROMAKS2 program of the Research Council of Norway (193062/S60).

Experimental Study of detailed flow phenomena

Detailed experiments necessary in order to learn the droplet / film behaviour and important for e.g. heat transfer and pressure fall. N-pentane used as a model fluid.

	Pentane (40°C)	**Liquid methane (-162 °C, NIST[1])**	**Water (20°C) (NIST [1])**
Density (kg/m^3)	606	422	998
Surface tension(N/m)	0.0137	0.0129	0.072
Viscosity (Pa/s)	$1.97 * 10^{-4}$	$1.12 * 10^{-4}$	$10 * 10^{-4}$
$Ga^{1/4}$	569	875	441
Ca (mm)	1.52	1.77	2.71

Coalescence-Splashing Threshold



$$We_c = \frac{2100 + 5800\Delta^{*1.44}}{Oh^{-0.4}}$$