From droplets to process:
Multilevel research approach to reduce emissions from LNG processes

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Per Eilif Wahl
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 reliability have big impact!
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.
Low-Emission LNG Overview

SP3: LNG processes

SP2: Heat exchanger modeling

SP1: Two-phase flow phenomena

Detailed heat exchanger model

Robust modeling framework

HX understanding

HX 2-phase flow distr. and instabilities

Flow map

Modeling

Verification

Understanding

Experiments

Scale

Photo: The Linde group
Low-Emission LNG Overview

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

Example: water droplets on water pool
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

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• Droplet falling in deep pool

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- 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
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- Study of different regimes of flow falling on cylinders
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• 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 discontinuous curvature

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 discontinuous curvature
- Model-experiment comparison for droplet-film coalescence possible
Modeling of detailed flow phenomena

- Based on level-set method to track interfaces
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- Describes droplet-film coalescence
- Heat and mass transfer
Modeling of detailed flow phenomena

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

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
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

- Currently implemented: Shell & tube, plate-fin

Heat Exchanger Modeling

FLEXHx: A Flexible Heat Exchanger Network - Robustness

Heat balance $100x(Q_{\text{warm}}-Q_{\text{cold}})/Q_{\text{cold}}$

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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

FLEXHx: A Flexible Heat Exchanger Network: Instabilities

Two solutions:

Blue: Metal temperatures
Red: Stream temperatures

G. Skaugen
TGTC3
Session A5
Heat Exchanger Modeling

Junction flow modeling: Looking at dynamic effects

Gunhild Allard Reigstad: Mathematical Modelling of Fluid Flows in Pipe Networks, PhD, April 2014
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- Detailed heat exchanger model

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SP1: Two-phase flow phenomena
- Modeling
- Verification
- Understanding
- Experiments

Flow map

Scale

Photo: The Linde group
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

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

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LNG Process optimization:

- 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


*) Shared acknowledgment with Remote Gas
Publications (more)

- 5 more scientific articles under peer-review
- **Two PhDs completed:**
  - 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

Acknowledgments

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).
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Coalescence-Splashing Threshold

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

- Coalescing \( n \)-pentane droplets
- Splashing \( n \)-pentane droplets
- Cossali c-s threshold
- Adjusted normal We corrected threshold