INTEGRATED ENERGY STORAGE TANK FOR LARGE SCALE POWER-TO-GAS APPLICATIONS

Master’s thesis
In collaboration with VTT, LUT and Fortum Foundation

Hannu Karjunaen 1.6.2015
CONTENTS

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Concept

- LNG tank
  - CO₂ storage (solid)
  - O₂ storage (external?)
  - Integration with an oxy-fuel combustion plant
- Large scale energy storage (electrolysis-methanation process)
- CO₂ looping

![Diagram of the process]

**NEO CARBC ENERGY**
Operation conditions

**Methane** – stored in liquid form, small portion in vapour form

**Carbon dioxide** – desublimation from gas to solid

- CO$_2$ pressure range limited
Boil-off gas (BOG)

- LNG constantly evaporates
- Heat leaks $\rightarrow$ Evaporation $\rightarrow$ Pressure / Evacuation
- Temperature remains constant
Boil-off gas (BOG)

- $\text{CO}_2$ increases BOG generation
  - Sensible heat contained in gas
  - Latent phase change
  - Sensible heat of solid phase

![Graph showing pressure vs. temperature with various curves]

**NEO Carbon Energy**
Rollover

- **Stratified layers**
  - Density
  - Temperature

- **Causes rapid BOG generation**
  - Structural damage to tank
OBJECTIVES & METHODOLOGY
Main objectives

- Developing a CFD model capable of...
  - Modelling the boil-off phenomenon (BOG)
  - Modelling the desublimation of carbon dioxide
- What kind of effects / flow fields the feeding of carbon dioxide could cause?
- Feasibility?
- Challenges?
- Introduction of related studies and literature
Methodology

- Transient CFD axisymmetric simulation performed using ANSYS Fluent
  - Methane: two-phase simulation
  - CO₂ desublimation: source terms
- Thermodynamic analysis
  - Boundary values for simulations
  - General feasibility
  - Comparison
Model details

- Heat leaks from literature
- CO₂ fed to the bottom section of the tank (source terms)
- Evaporation model defined by a user-defined function:
  - Computational cell temperature compared to saturation temperature
    → Not restricted by location
  - Mass transfer between liquid and vapour phases
  - Heat source term used to model the latent heat
    → Causes natural convection in the liquid

Floor: 45 %
Roof: 15 %
40%
RESULTS
Thermodynamic evaluation

• Assumptions:
  – Site is connected to an 230 MW\textsubscript{th} oxy-fuel combustion plant
  – Flue gases (CO\textsubscript{2}) have been precooled to sublimation temperature (~190K)

• Process in simplified form:
  1. Evaporate methane and oxygen (stored as liquid)
  2. Combustion
  3. Desublimate produced flue gases to solid (CO\textsubscript{2})

• Desublimation would require more “cold” than is available from evaporation of methane and oxygen
Boil-off model

• Boil-off model functioned, but did not fully agree with thermodynamic energy balance calculations

• Causes:
  ▪ Model coefficient
  ▪ Pressure condition
  ▪ Cell size at the liquid surface

<table>
<thead>
<tr>
<th>Portion of flue gases fed to tank</th>
<th>Boil-off rate (BOR) from simulations</th>
<th>BOR from thermodynamic energy balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kg/s</td>
<td>kg/s</td>
</tr>
<tr>
<td>0</td>
<td>~ 0.05 - 0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>25</td>
<td>~ 0.5</td>
<td>4.3</td>
</tr>
<tr>
<td>50</td>
<td>~ 1.2</td>
<td>8.2</td>
</tr>
<tr>
<td>100</td>
<td>-</td>
<td>16.4</td>
</tr>
</tbody>
</table>
CO$_2$ feeding

- Initial study without CO$_2$ feeding
- With CO$_2$ feeding, the main difference was higher velocity magnitudes (flow fields similar)
- Still unclear: how the deposition affects the flow in a smaller scale? (effect of momentum, pressure variations…)
- Deposition model is heavily simplified
Momentum source term drives the flow along tank floor

Natural convection lifts the flow along the middlesection

Two slightly different flow fields:
Rollover

• Rollover evaluation is challenging – even without CO₂ addition
• Unique phenomena in stratified layers (diffusive convective flow, penetrative convection…) which are problematic to model
• Pressure, composition, tank specifications…
• Previous models are generally lumped, ”bulk” models
Conclusions

- Time delay between initiating CO\textsubscript{2} feeding and observing a change in boil-off rate is measured in minutes \(\rightarrow\) Buffer potential for tank is minimal

Case 0: No CO\textsubscript{2} feed
Case 1: 25 % CO\textsubscript{2} feed
Case 2: 50 % CO\textsubscript{2} feed

The CO\textsubscript{2} feeding was increased linearly from 0 to 100 % (during 100s)
Conclusions

• Amount of CO$_2$ fed into the tank needs to be restricted (otherwise more LNG is evaporated than could be processed by the power plant)

→ Natural gas grid integration?
→ Complete cycle simulation

\[
\begin{align*}
\text{CO}_2 & \text{ flue gas} \\
8.8 \text{ [MW]} & \\
\text{CH}_4 & 28.4 \% \\
\text{O}_2 & 44.3 \% \\
\text{Other} & 2 \text{ [MW]} 27.3 \% 
\end{align*}
\]
Conclusions

- Further models require information on **direct contact desublimation with a cryogenic liquid**, literature on subject is scarce (can be found for gases as the working medium, but not with liquids)
- Pressure < 5 bar to prevent liquid CO$_2$ formation
Recommendation for further work

- Properties and formation of dry ice, especially in a desublimation process with different pressures
- Cycle integration: how to match evaporation and desublimation between the substances, "dynamic storage"
- Interaction of the cryogenic liquid/gas/solid
  - Momentum transfer, movement, lumps vs particles…
- Rollover tests / validation / BOG handling capacity
THANK YOU!
EXTRA SLIDES
Potential benefits

• Simple construction
• Utilization of latent heat between phase changes → Cycle optimization
• Based on existing LNG infrastructure
• Integrates the CO$_2$ separation process (CO$_2$ looping)
Rollover

- Rollover is a danger encountered in conventional LNG tanks
- Caused mainly by the different composition of LNG batches (tank refill)
- Layers have different temperature and densities → Rollover occurs when density difference diminishes
- Large amount of warm liquid transfers to the surface → Large amount of BOG generated → Potential damage to tank due to pressure increase
- LNG tanks equipped with systems capable of breaking stratified layers and pumping liquid from one layer to another
Desublimation model

Functioned well, but…

- Observed changes in flow patterns were quite small (different configurations were not tested)
- Requires more detailed information about the deposition region (e.g. pressure effects, reaction rate, small-scale effects…)
- Is currently restricted by location, complex configurations could be tedious to implement (requires mesh modification i.e. distinct zones)
- Future models could also model CO$_2$ as a real substances (and not as source terms)
Remarks

- Some mass "disappeared" from the tank during simulations
- Relative amount rather small (in the region of < 0.1 ‰), although this varied between simulations
- Was not considered to have a critical effect on results
- Possible contributors:
  - Pressure boundary conditions
  - Boil-off model
  - Computational mesh
Flow patterns

- Preliminary study was done **without CO₂ feeding**
- Initially flow travelled up along the outer wall of the tank
- Later the flow reversed: flow travelled down along the outer wall and up the middle section
- Probably caused by the large heat leak of the flooring → Further verification should be conducted on how the heat leaks distribute among different wall sections