BREATHING LOSSES FROM LOW-PRESSURE STORAGE TANKS DUE TO ATMOSPHERIC WEATHER CHANGE

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Agenda

1. Introduction
2. State of the art
3. Description of available models and experiments
4. Conclusions
5. Future work
Introduction

- Low-pressure tanks are large open-air storage tanks, containing huge amounts of product within thin walls

- Protection against corrosion and thermal losses caused by weather changes incl. storms is often done by organic coating

- A more economical corrosion protection may be painting the tank. However, a painted tank lacks of the thermal protection against weather temperature changes or seasonal rainfalls or droughts

- For a tank protected against vacuum and overpressure ambient heat inflow leads to breathing out of valuable product, whereas sudden cooling leads to vacuum, compensated by in-breathing of ambient air.
State of the art

- Literature sources on this topic

  - „Naumann formulas“ (unpublished)
State of the art / Models and experiments

<table>
<thead>
<tr>
<th>Model</th>
<th>Model</th>
<th>Experiments</th>
<th>Applicability (Case study)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naumann (unpublished)</td>
<td>Empirical</td>
<td></td>
<td>Thermal tank heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Thermal tank cooling</td>
</tr>
<tr>
<td>Höchst / Sigel et al. (1983)</td>
<td>Analytical</td>
<td>Rain cooling on Air tank (600 m³)</td>
<td>Short rainfalls</td>
</tr>
<tr>
<td>PTB / Förster et al. (1984)</td>
<td>Analytical</td>
<td></td>
<td>Long sun exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Short and long rainfalls</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Condensing tank products</td>
</tr>
<tr>
<td>Salatino (1999)</td>
<td>Analytical</td>
<td></td>
<td>Sudden rain falls</td>
</tr>
</tbody>
</table>

**Note:** The methods (measurements) presented here have been derived (performed) for **cylindrical tanks**
Naumann formulas

Naumann formulas are **conservative** empirical estimations of the tank maximum in- and outbreathing to compensate for tank thermal heating and cooling.

\[
\dot{V}_{\text{max-out}} = 1.1 \frac{m}{h} \cdot H \cdot D \approx 1.292 \frac{m}{h} \cdot \left( \frac{H}{D} \right)^{1/3} \cdot (V_{\text{tank}})^{2/3}
\]

\[
\dot{V}_{\text{max-in}} = 1.5 \frac{m}{h} \cdot (H + 4D) \cdot D \approx 1.762 \frac{m}{h} \cdot \left[ 4 \left( \frac{H}{D} \right)^{-2/3} + \left( \frac{H}{D} \right)^{1/3} \right] (V_{\text{tank}})^{2/3}
\]
PTB tank heating model

Tank volume increment following a long sun exposure

\[
\dot{V}_B(t) = \frac{V_{tank}}{T_{B0}} \frac{c}{\lambda} \left[ \exp \left( \frac{\lambda - a}{2} t \right) - \exp \left( - \frac{\lambda + a}{2} t \right) \right]
\]

\[
\lambda = \sqrt{a^2 - 4b}
\]

\[
a_{PTB} = A_{tank} \left( \frac{\alpha_B}{C_B} + \frac{\alpha_B + \alpha_{conv} + 0.75 \varepsilon_{emis} \alpha_{emis}}{C_E} \right)
\]

\[
b_{PTB} = A_{tank}^2 \frac{\alpha_B}{C_B} \cdot \frac{\alpha_{conv} + 0.75 \varepsilon_{emis} \alpha_{emis}}{C_E}
\]

\[
c_{PTB} = A_{tank}^2 \frac{\alpha_B}{C_B} \cdot \frac{l \cdot \varepsilon_{rad} \Phi_{GEOM} - 0.5 \cdot E_{BLACK} \varepsilon_{emis}}{C_E}
\]

This formula foresees a maximum tank shrinking \( V_{max} \) at some time

\[
\dot{V}_{max} = \dot{V}_B(\tau) \quad \text{with} \quad \tau = \frac{1}{\lambda} \ln \left( \frac{a + \lambda}{a - \lambda} \right) \neq 0
\]
Höchst and PTB tank cooling model

Tank volume reduction following rainfall cooling

\[
\dot{V}_B(t) = V_B \cdot \frac{T_B - T_{\text{rain}}}{T_B} \cdot \frac{b}{\lambda} \left[ \exp \left( \frac{\lambda - a}{2} t \right) - \exp \left( -\frac{\lambda + a}{2} t \right) \right]
\]

\[
\lambda = \sqrt{a^2 - 4b}
\]

\[
a = A_{\text{tank}} \cdot \left( \frac{\alpha_B}{C_B} + \frac{\alpha_B + \alpha_w}{C_E} \right)
\]

\[
b = A_{\text{tank}}^2 \cdot \frac{\alpha_B}{C_B} \cdot \frac{\alpha_w}{C_E}
\]

Unlimited rain (flood, deluge)
Thin rain film thickness (rain)

This formula foresees a maximum tank shrinking \(\dot{V}_{\text{max}}\) at some time

\[
\dot{V}_{\text{max}} = \dot{V}_B(\tau) \quad \text{with} \quad \tau = \frac{1}{\lambda} \ln \left( \frac{a + \lambda}{a - \lambda} \right) \neq 0
\]

\[
k = \frac{\alpha_w}{\alpha_w + \dot{m}_{\text{rain}} c_{\text{rain}}}
\]
Salatino model

- It considers the different heat transfer intensity between gas and tank shall and the roof in a partially filled wetted tank. Liquid temperature is assumed unchanged.

- His method consists in a thermodynamic analysis of the tank before and after a weather change, f.i. rainfall cooling in a long hot dry summer.

- Final gas temperature in function of the final temperature of each surface facing it:

\[
T_{end,G} = \sum \frac{A_i \cdot \alpha_{iG} \cdot T_i}{A_i \cdot \alpha_{iG}} = \frac{A_r \cdot \alpha_{rG} \cdot T_r + A_s \cdot \alpha_{sG} \cdot T_s + A_L \cdot \alpha_{LG} \cdot T_L}{A_r \cdot \alpha_{rG} + A_s \cdot \alpha_{sG} + A_L \cdot \alpha_{LG}}
\]

- He proposed a rigorous numerical method and a simplified model to predict the maximum inbreathing load due to rainfall cooling of a warm tank (Difference 2%):

\[
\dot{V}_{tank} = \frac{R}{p} \cdot (T_{hot,G} - T_{cold,G}) \cdot \frac{A_r \cdot \alpha_{rG} + A_s \cdot \alpha_{sG} + A_L \cdot \alpha_{LG}}{c_p}
\]
ISO 28300 and API 2000 (2009)

- The thermal outbreathing capacity is given by
  \[ \dot{V}_{out} = Y \cdot (V_{tank})^{0.9} \cdot R_i \]

- The thermal inbreathing capacity is given by
  \[ \dot{V}_{in} = C \cdot (V_{tank})^{0.7} \cdot R_i \]

### Y Factor

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Y Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 42°</td>
<td>0.32</td>
</tr>
<tr>
<td>Between 42° and 58°</td>
<td>0.25</td>
</tr>
<tr>
<td>Above 58°</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Vapor Pressure

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Storage temperature</th>
<th>C Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vapor pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hexane or similar</td>
<td>C Factor</td>
</tr>
<tr>
<td></td>
<td>Higher than hexane, unknown</td>
<td>C Factor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Below 25°C</th>
<th>Above 25°C</th>
<th>Below 25°C</th>
<th>Above 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below 42°</td>
<td>4</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>42° - 58°</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Above 58°</td>
<td>2.5</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

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PROTEGO® Initial test / Test condition and sensors

**Tank data**
- Tank diameter: 1.15 m
- Tank length: 4.3 m
- Tank volume: 4.466 m³
- Wall thickness: 10 mm
- Medium in the tank: Air

**Test environment**
- Wall temperature: 55°C

**Sensors and measuring equipment**
- Anemometer Testo 452 (max. 20 m/s; accuracy ± 0.5 m/s)
- Test probe diameter 12 mm
- Inner Temperature Thermometer Pt100
- Outer Temperature Thermocouple

Water poured using two hoses with combined mass flux of 230 kg/m²h
PROTEGO® Initial test / Temperature profiles and inbreathing velocity

- Ambient air temperature: 12°C
- Barometric pressure: 1.006 bar

Max. air velocity: 17.3 m/s

Inner temperature
Air velocity
Outer temperature

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Conclusions about the available data

- Besides ISO 28300 (API 2000), PTB and Höchst models enjoy wide acceptance

- Models have been validated for either gassy or laboratory size tanks

- The tanks are considered as uninsulated and the impact of wall thickness is unaccounted

- Some models predict the maximum inbreathing load occurring as soon as rain falls, while others assume it occurring later on

- Models often rely heavily on simplified assumptions for heat transfer coefficients, see f. i. constant temperature – independent convection coefficients

- Furthermore, most models use convection heat transfer coefficients derived for small diameter piping systems to tanks.

- Inner tank vapor condensation mechanism is usually neglected (Nucleation)
Future work / Targets for future research

- Measurements will be started with small tanks: test tank (4.3 m²) to API 12F (62 m²)
- Measurements with hot air, ethanol, methanol
- Filling levels: 10%, 50%, 75%, 90%
- Natural precipitation or water pouring with hoses
- Modeling product condensation (nucleation models), tank wall thickness and insulation

These are our ideas!
We are open for suggestions, critics and inputs
Work in Progress / Roadmap

- 10th European Congress Chemical Engineering, [www.ecce.eu](http://www.ecce.eu)
  27. Sept. – 01. Oct. 2015, Nice, France, accepted paper

- DIERS Fall 2015 Meeting,
  05. – 07. Oct. 2015, Houston, TX, USA

  05. – 08. June 2016, Freiburg, Germany, accepted paper

- DIERS Spring 2016, tbd
Thank you very much for your kind attention!

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