A new thermodynamic system for LNG cold energy recovery in its gasification process

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Presented by: Prof. Zhiguo Qu
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1. Research background

Natural Gas

Transmission

- The Soviet Union: 30.8%
- Central and South America: 4%
- North America: 4.8%
- Asia-Pacific: 8.3%
- Africa: 7.9%
- European and Eurasian Continental: 35.69%
- Middle East: 11.67%
- Central and South America: 4.69%
- North America: 26.82%
- Middle East: 3.29%
- Asia-Pacific: 17.85%
LNG Vaporizer

Open Rack Vaporizer

Submerged Combustion Vaporizer

Intermediate Fluid Vaporizer
LNG Cold Energy Utilization

- Air separation
- Light hydrocarbon separation
- Power generation
- Liquid/Solid CO₂ production
- Cryogenic warehousing
- Seawater desalination
- Cryogenic pulverization
2. Physical and mathematical model

Proposed energy system

T-S diagram
$\phi_{14i} = H_{P4i} - H_{P4(i-1)}; i = 2 \sim N_{P14}$

$\phi_{14i}^* = A_{14i} k_{14i} \Delta T_{14i}; i = 2 \sim N_{P14}$

$\phi_{14i} = \phi_{14i}^*; i = 2 \sim N_{P14}$

$\phi_{13i} = H_{P3i} - H_{P3(i-1)}; i = 2 \sim N_{P13}$

$\phi_{13i}^* = A_{13i} k_{13i} \Delta T_{13i}; i = 2 \sim N_{P13}$

$\phi_{13i} = \phi_{13i}^*; i = 2 \sim N_{P13}$
Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education

Evaporator

Propane $T_{P3} q_{m3}$

Seawater $T_{wa6} q_{m1}$

Seawater $T_{wa2} q_{m1}$

Propane $T_{P1} q_{m3}$

|x| $h = 0.023 Re^{0.8} Pr^{0.3} \left( \frac{\lambda}{d_i} \right)$
|---|---|
|0 $< x < 0.8$| $h_{tp} = \frac{3.0}{X_{tt}^{2/3}}$ $h_L = 0.023 \left( \frac{\lambda_i}{d_i} \right) \left( \frac{d_i V_m}{\mu_i} \right)^{0.8} Pr_i$
|0.8 $\leq x \leq 1.0$| $h_p = h_{do} - \frac{h_{do} - h_g}{1.0 - x_{do}} (x - x_{do})$
|x $> 1.0$| $h_g = 0.023 (\lambda_v / d_i) (d_i V_m / \mu_v)^{0.8} (Pr_v)^{0.4}$

$Nu_f = \begin{cases} 
1.04 \left( \frac{S_1}{S_2} \right)^{0.2} Re_f^{0.4} Pr_f^{0.36} \left( \frac{Pr_f}{Pr_w} \right)^{0.25}, & 1 < Re < 10^2 \\
0.71 \left( \frac{S_1}{S_2} \right)^{0.2} Re_f^{0.5} Pr_f^{0.36} \left( \frac{Pr_f}{Pr_w} \right)^{0.25}, & 5 \times 10^2 < Re < 10^3 \\
0.35 \left( \frac{S_1}{S_2} \right)^{0.2} Re_f^{0.6} Pr_f^{0.36} \left( \frac{Pr_f}{Pr_w} \right)^{0.25}, & 2,10^3 < Re < 2 \times 10^5 \\
0.40 \left( \frac{S_1}{S_2} \right)^{0.2} Re_f^{0.6} Pr_f^{0.36} \left( \frac{Pr_f}{Pr_w} \right)^{0.25}, & 2,10^5 < Re < 2 \times 10^5 \\
0.031 \left( \frac{S_1}{S_2} \right)^{0.2} Re_f^{0.8} Pr_f^{0.36} \left( \frac{Pr_f}{Pr_w} \right)^{0.25}, & 2 \times 10^5 < Re < 2 \times 10^6 \\
\end{cases}$

8/27
Propane vapor $T_{p3}$

$$\phi_{2i} = H_{2i} - H_{2(i-1)}; i = 2 \sim N_{L2}$$

$$\phi_{2i}^* = A_{2i} k_{2i} \Delta T_{2i}; i = 2 \sim N_{L2}$$

$$\phi_{2i} = \phi_{2i}^*; i = 2 \sim N_{L2}$$

Condenser

$$Nu = 0.021Re^{0.82} Pr^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{C_p}{C_{pb}} \right)^n$$

$$h = 0.79 \left[ \frac{gr \rho_l (\rho_l - \rho_g) \lambda_q^3}{\mu_l d (t_s - t_w)} \right]^{0.25}$$
seawater \((T_{w1} + T_{w2})/2\)

\[
T_{L3(i-1)} q_m \rightarrow \text{NG} \rightarrow \phi_{3i} \rightarrow T_{L3i} q_m \rightarrow \text{NG}
\]

seawater \((T_{w1} + T_{w2})/2\)

\[
\phi_{3i} = H_{3i} - H_{3(i-1)}; i = 2 \sim N_{L3}
\]

\[
\phi_{3i}^* = A_{3i} k_3 \Delta T_{3i}; i = 2 \sim N_{L3}
\]

\[
\phi_{3i} = \phi_{3i}^*; i = 2 \sim N_{L3}
\]

\[
Nu_f = \begin{cases} 
1.04 \text{Re}^{0.4} \text{Pr}_f^{0.36} \left( \text{Pr}_f/\text{Pr}_w \right)^{0.25}, & 1 < \text{Re} < 10^2 \\
0.71 \text{Re}^{0.5} \text{Pr}_f^{0.36} \left( \text{Pr}_f/\text{Pr}_w \right)^{0.25}, & 5 \times 10^2 < \text{Re} < 10^3 \\
0.35 \left( \frac{s_1}{s_2} \right)^{0.2} \text{Re}_f^{0.6} \text{Pr}_f^{0.36} \left( \text{Pr}_f/\text{Pr}_w \right)^{0.25}, & \frac{s_1}{s_2} \leq 2, 10^3 < \text{Re} < 2 \times 10^5 \\
0.40 \text{Re}_f^{0.6} \text{Pr}_f^{0.36} \left( \text{Pr}_f/\text{Pr}_w \right)^{0.25}, & \frac{s_1}{s_2} > 2, 10^3 < \text{Re} < 2 \times 10^5 \\
0.031 \left( \frac{s_1}{s_2} \right)^{0.2} \text{Re}_f^{0.8} \text{Pr}_f^{0.36} \left( \text{Pr}_f/\text{Pr}_w \right)^{0.25}, & 2 \times 10^5 < \text{Re} < 2 \times 10^6
\end{cases}
\]

\[
Nu = 0.021 \text{Re}^{0.82} \text{Pr}^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{C_p}{C_{pb}} \right)^n
\]
Assumptions

- The flow is steady
- The system is well insulated with ambient
- Pressure drop in pipe lines is neglected
- The mass flow is distributed uniformly in each tube in the heat exchanger
- Methane is used to instead of LNG and water is used to instead of seawater
The known default parameters

Operating parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$T_{wa1}$</th>
<th>$q_{m1}$</th>
<th>$q_{m2}$</th>
<th>$T_{L,1}$</th>
<th>$A_1$ evaporator</th>
<th>$A_2$ condenser</th>
<th>$A_3$ thermolater</th>
<th>$P_L$</th>
<th>$P_{wa}$</th>
<th>$P_{P2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>K</td>
<td>kg·s⁻¹</td>
<td>kg·s⁻¹</td>
<td>K</td>
<td>m²</td>
<td>m²</td>
<td>M²</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>Default value</td>
<td>293.15</td>
<td>1000</td>
<td>30</td>
<td>108.0</td>
<td>1500</td>
<td>500</td>
<td>300</td>
<td>12.0</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The known geometric parameters of exchangers

<table>
<thead>
<tr>
<th>Geometric parameter</th>
<th>Value</th>
<th>Geometric parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The length of heat tubes in evaporator</td>
<td>16/m</td>
<td>Outer diameter of heat tubes</td>
<td>0.02/m</td>
</tr>
<tr>
<td>The length of heat tubes in condenser</td>
<td>14/m</td>
<td>Internal diameter of heat tubes</td>
<td>0.016/m</td>
</tr>
<tr>
<td>The length of heat tubes in thermolator</td>
<td>4/m</td>
<td>The area of flow channel inside that seawater flows across the tube banks</td>
<td>1/m²</td>
</tr>
</tbody>
</table>
The predicted parameters

The parameters that would be calculated in the paper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nomenclature</th>
<th>Parameter</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>The temperature of seawater</td>
<td>$T_{wa}$</td>
<td>Heat transfer in evaporator</td>
<td></td>
</tr>
<tr>
<td>The temperature of LNG</td>
<td>$T_L$</td>
<td>Total</td>
<td>$k_1$</td>
</tr>
<tr>
<td>The temperature of propane</td>
<td>$T_P$</td>
<td>Inside tube</td>
<td>$h_{1I}$</td>
</tr>
<tr>
<td>Heat transfer in condenser</td>
<td></td>
<td>Outside tube</td>
<td>$h_{1O}$</td>
</tr>
<tr>
<td>Heat transfer in thermolator</td>
<td></td>
<td>Total</td>
<td>$k_3$</td>
</tr>
<tr>
<td>Thermal efficiency of ORC</td>
<td>$\eta$</td>
<td>Heat transfer in thermolator</td>
<td>$h_{3I}$</td>
</tr>
<tr>
<td>Net output power of ORC</td>
<td></td>
<td>Outside tube</td>
<td>$h_{3O}$</td>
</tr>
</tbody>
</table>
\[ W_{\text{net out}} = W_{\text{out}} - W_P \]

\[ \eta = \frac{(H_{P_1} - H_{P_2}) - (H_{P_4} - H_{P_3})}{(H_{P_1} - H_{P_4})} = \frac{W_{\text{out}} - W_P}{\phi_1} = \frac{W_{\text{net out}}}{\phi_1} \]
Thermal property

Methane and propane: REFPROP

Water: PROPATH
Solution methods

Start

Input the known parameters

Assume $P_{in}, T_{in2}$

Solve the state parameters of propane in thermolator

Sub-set of condenser

Solve the distribution of LNG temperature in condenser

Solve $q_{in}$ according the conservation of energy relation in condenser

Solve $T_{in}$ and $T_{in2}$ according $T_{in2}$ and conservation of energy relation in thermolator

Sub-set of thermolator

Solve the distribution of LNG temperature in thermolator

Solve $T_{in2}$

Judge the conservation of heat in thermolator

Solve statue parameters of propane in evaporation process

Sub-set of evaporator

Solve the distribution of propane temperature in evaporator

Judge the conservation of heat in evaporator

Solve $P_{in}$

Output the results

End
Grid independence verification

Evaporator

Condenser

Thermolator
3. Results and discussion

Predicted values at default conditions

\[ W_{\text{netout}} = 1575.77/\text{kW} \]

\[ \eta = 7.8\% \]
Temperature distribution of seawater

The distribution of seawater temperature

- $T_{\text{wal}} = 303.15 \text{ K}$
- $T_{L1} = 118.00 \text{ K}$
- $q_{m1} = 1500 \text{ kg/s}$
- $q_{m2} = 45 \text{ kg/s}$
- $P_{P2} = 0.4 \text{ MPa}$
Temperature distribution of natural gas

The distribution of natural gas temperature

In thermolator only:

- $T_{wa1} \uparrow \rightarrow T_L \uparrow$
- $q_{m1} \uparrow \rightarrow T_L \uparrow$

Whole section:

- $T_{L1} \uparrow \rightarrow T_L$
- $q_{m2} \uparrow \rightarrow T_L \downarrow$
- $p_{P2} \uparrow \rightarrow T_L \uparrow$
Temperature distribution of propane

In evaporator only:

- $T_{\text{Wal}} \uparrow \rightarrow T_P \uparrow$
- $T_{L1} \uparrow \rightarrow T_P \uparrow$
- $q_{m1} \uparrow \rightarrow T_P \uparrow$

Whole section:

- $P_{P2} \uparrow \rightarrow T_P \uparrow$

The distribution of propane temperature

- $T_{\text{Wal}} = 303.15 \text{ K}$
- $T_{L1} = 118.00 \text{ K}$
- $q_{m1} = 1500 \text{ kg/s}$
- $q_{m2} = 45 \text{ kgs}$
- $P_{P2} = 0.4 \text{ MPa}$

Condenser

Evaporator
HTC distribution in evaporator

- $T_{wa1} = 303.15$ K
- $T_{L1} = 118.00$ K
- $q_{m1} = 1500$ kg/s
- $q_{m2} = 45$ kg/s
- $P_{P2} = 0.4$ MPa

- $T_{wa1} \uparrow \{h_{11}, h_{1O}\} \uparrow k_1$
- $T_{L1} \uparrow \{h_{11}\} \uparrow k_1$
- $q_{m1} \uparrow \{h_{11}, h_{1O}\} \uparrow k_1$
- $q_{m2} \uparrow \{h_{11}\} \uparrow k_1$
- $P_{P2} \uparrow \{h_{11}\} \downarrow k_1$

$h_{1O}$
HTC distribution in condenser

$\begin{align*}
T_{\text{wal}} & = 303.15 \text{ K} \\
T_{L1} & = 118.00 \text{ K} \\
q_{m1} & = 1500 \text{ kg s}^{-1} \\
q_{m2} & = 45 \text{ kg s}^{-1} \\
P_{P2} & = 0.4 \text{ MPa}
\end{align*}$

$\begin{align*}
T_{\text{wa1}} & \uparrow \left\{ \begin{array}{c} h_{21} \\ h_{2O} \end{array} \right\} k_1 \\
T_{L1} & \uparrow \left\{ \begin{array}{c} h_{21} \\ h_{2O} \end{array} \right\} k_1 \\
q_{m1} & \uparrow \left\{ \begin{array}{c} h_{21} \\ h_{2O} \end{array} \right\} k_1 \\
q_{m2} & \uparrow \left\{ \begin{array}{c} h_{21} \\ h_{2O} \end{array} \right\} k_1 \\
P_{P2} & \uparrow \left\{ \begin{array}{c} h_{21} \\ h_{2O} \end{array} \right\} k_1
\end{align*}$
HTC distribution in thermolator

- $h_3$ [W/m²·K]
- $h_3$ [W/m²·K]
- $h_3$ [W/m²·K]

Parameters:
- $T_{wa1}$ = 303.15 K
- $T_{L1}$ = 118.00 K
- $q_{m1}$ = 1500 kg/s
- $q_{m2}$ = 45 kg/s
- $P_{P2}$ = 0.4 MPa

Graphs showing HTC distribution with varying parameters.
Thermal efficiency and net output power

The effects of parameters on thermal efficiency and net output power

- $T_{wa1}$: $\uparrow$ $\rightarrow$ $\eta$ $\uparrow$; $W_{netout}$ $\uparrow$
- $T_{L1}$: $\uparrow$ $\rightarrow$ $\eta$ $\uparrow$; $W_{netout}$ $\downarrow$
- $q_{m1}$: $\uparrow$ $\rightarrow$ $\eta$ $\uparrow$; $W_{netout}$ $\uparrow$
- $q_{m2}$: $\uparrow$ $\rightarrow$ $\eta$ $\uparrow$; $W_{netout}$ $\uparrow$
- $P_{P2}$: $\uparrow$ $\rightarrow$ $\eta$ $\uparrow$; $W_{netout}$ $\uparrow$
4. Conclusions

1. A one-dimensional heat transfer model and thermodynamic model for the hybrid system with LNG and ORC for LNG cold energy utilization was proposed.

2. The energy system successfully realize the LNG vaporization LNG cold energy recovery for net power.

3. The effect of various parameter on performance of the whole system were obtained.

4. The thermal efficiency for ORC is sensitive to sea water inlet temperature and propane condensation pressure.
Thank you for your attention!