Analysis of the LNG re-condensation system based on Joule-Thomson cooler

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Abstract. Nowadays, LNG (Liquefied Natural Gas) has become a significant alternative fuel for both land and marine transport units. Due to formal regulations, gaseous natural gas (boil-off gas - BOG) cannot be released to environment when e.g. ship is docked or truck is out of operation. Stream of BOG can be burnt but this solution should be limited due to ecological reasons. Therefore, re-condensation systems allowing to extend holding time of the storage vessels are currently under strong interest and development. Joule-Thomson (J-T) cooler is simple cryogenic system, well recognized and tested. However, J-T coolers are not commercially available mainly because of very high working pressure and low thermodynamic efficiency. Both problems can be reduced by using gas mixture instead of single component working fluid. This paper presents thermodynamic analysis of the LNG re-condensation system based on Joule-Thomson cooler working in the closed system and supplied with gas mixture. Optimization analysis of the working mixture are presented. Theoretical results have been experimentally verified. Test results are presented and discussed.

1. Introduction
LNG (Liquefied Natural Gas) becomes the fuel of the future in the heavy and marine transportation. The natural gas is one of the cleanest and eco-friendly fuel, which may be used instead of conventional fuels based on the petroleum derived fuels [1]. The International Marine Organization has approved the Emission Controlled Areas, where the pollution from marine transportation is strongly limited. The regulations covers the Baltic and North Sea in Europe and the coasts of North America. Moreover, it is planned to include additional areas in the near future. Considering that, the number of the LNG fueled ships will be increased, as can be seen in recent years.

The natural gas is stored as a liquid, what allows to reduce the volume of the fluid around 700 times in comparison to the natural gas in ambient conditions. However, the low temperature of the LNG (around 111 K) enforces using the cryogenic tanks and devices. Due to a heat leak to the LNG the pressure in the tank rises and the fuel evaporates. The evaporated fuel is called as boil-off gas (BOG). After exceeding the permissible pressure, the fuel must be released through the safety valve [2]. However, methane (the main component of the LNG) is one of the main greenhouse gas thats emission to atmosphere is prohibited. In some cases, one of the economically substantiated ways is to liquefy the BOG. However, existing systems are based on the expensive, complicated and large installations. That is why the interest in Joule-Thomson coolers to BOG re-liquefaction is growing. The main advantage of such cooler
is simple construction, lack of the moving part in the cold stage, relatively low investment cost and high reliability [3]. The schematic diagram of the BOG liquefier with the J-T cooler fed with the gas mixture is presented in Fig. 1.

![Figure 1](image)

The BOG flows through the main cycle evaporator and it is liquefied non-isothermally, due to the content of the high boiling gases in the fuel. After the liquefaction process the liquid goes to the LNG tank.

2. Optimization of the working mixture

One of the key things is selection of the components and their molar fractions in the working mixture. The proper composition of the mixture has a significant impact on performance and efficiency of the cryocooler, what is strongly associated with subsequent operating costs. Nowadays, inert gases and hydrocarbons are used as the mixture components because they are environmentally friendly. However, the main disadvantage is that some components of the mixture are flammable. Nevertheless, in case of BOG re-liquefaction system, the flammability of the mixture is not a problem. In presented considerations the gases taken as a mixture components are: nitrogen, argon, methane, propane, ethane, ethylene, n-pentane, i-pentane, i-butane.

To optimize the composition and fraction of the individual components in the mixture, the gross cooling power of the J-T cooler can be calculated as [4]:

\[
g_{\text{gross}} = \Delta h_{\text{T,min}} (p, T) = h_2 (p_2, T) - h_1 (p_1, T)
\] (1)

The gross cooling power equals the isothermal minimum enthalpy difference for the low and high pressure stream in the whole temperature region of interest, unlike for pure component working fluids. In case of pure gas, the minimum enthalpy difference occurs always at the warm end of the heat exchanger, therefore, it is not required to consider the entire temperature range. For the mixtures, the minimum isothermal enthalpy difference may be in the whole temperature range [4, 5].

The J-T cooler fed with the gas mixture is built with the mass-produced components made for the refrigeration industry, so it was assumed that the operating pressure is 20 bar. This is the pressure reachable for the commercial compressors. A suction pressure was assumed as 1.1 bar, to provide slide overpressure on the suction line. The operating temperature region is from 100K (around 10K lower than methane normal boiling temperature) to the ambient temperature assumed as 300K, what corresponds to the ambient temperature. This assumption ensures the correct operation of the system regardless of the composition of BOG and pressure.

The optimization of the gas mixture was done using an algorithm presented in Fig. 2. Due to the very large number of combinations, in the case of mixtures of 5 and more components, the step \((r)\) should not be lower than 0.05. All the calculations are made in Python programming language.
The analysis was performed for all the combinations of gases. The results of the calculations are given in Tab. 1, where the compositions and gross capacities of the six chosen mixtures are provided.

Table 1. Molar composition of the selected mixtures and their gross capacity.

| No. | $N_2$ | $R-50$ | $R-170$ | $R-290$ | $R-601a$ | $R-1150$ | $R-600a$ | $Ar$ | $\Delta h_{T_{min}}$ |
|-----|-------|--------|---------|---------|----------|----------|----------|-----|-----------------|
| 1   | 0.35  | 0.30   | 0.15    | 0.05    | 0.00     | 0.00     | 0.00     | 0.15| 54.1            |
| 2   | 0.40  | 0.25   | 0.05    | 0.05    | 0.05     | 0.15     | 0.00     | 0.00| 59.7            |
| 3   | 0.40  | 0.30   | 0.05    | 0.05    | 0.05     | 0.10     | 0.00     | 0.00| 58.9            |
| 4   | 0.40  | 0.25   | 0.05    | 0.05    | 0.05     | 0.10     | 0.05     | 0.00| 52.3            |
| 5   | 0.30  | 0.30   | 0.05    | 0.05    | 0.05     | 0.10     | 0.05     | 0.05| 46.1            |
| 6   | 0.35  | 0.25   | 0.05    | 0.05    | 0.05     | 0.10     | 0.10     | 0.10| 46.5            |

The highest value of the gross capacity ($\Delta h_{T_{min}}$) is reached for the mixture 2 and 3 and it is above 58 kJ/kg. However, the mixture consists of 7 components, what may cause the problems with the preparing of the mixture. Mixture 1 consists of only 5 components and the gross capacity is around 54, what is less about 9% in comparison with mixtures 2 and 3. Capacity of mixture 4 is comparable with mixture 1, but 8 gases are used in this mixture. Mixture 5 and 6 are characterized by the lowest gross capacity (around 46 kJ/kg). It is caused by too small amount of nitrogen (mixture 5) and methane and ethylene (mixture 6). In general it should be noted that, the total amount of low boiling gases as nitrogen, methane and argon in every mixture is higher than 0.65. The rest of the mixtures are the high boiling components in different combinations.

To check the theoretical analysis, the experiment was done to proof that the require temperature is possible to reach. Mixture 1 was used to the experimental verification, due to relatively high gross efficiency and the lowest number of components in the working mixture.

3. The test stand and the results

3.1. Test stand

The J-T cryocooler can be divided into three systems: oil cooling, refrigeration and cryogenic. The refrigeration and oil cooling system are build using mass produced components made for refrigeration industry and operates in the temperatures closed to the ambient temperature. The cryogenic system is placed in the vacuum chamber to minimize the heat flux to the low temperature components. The scheme of the J-T cooler is presented in Fig. 3.

The refrigeration system was built by components made for refrigeration industry. To compress the gas an oil lubricated reciprocating compressor was used - Danfoss Maneurop MTZ80. To provide proper oil separation, three separators connected in series was used.
conventional, helical and coalescent respectively. As the aftercooler a lamellar heat exchanger 
was used. The oil cooling system was built using oil filter, pump and the heat exchanger. The 
main purpose of the oil cooling system is to reduce the discharge temperature to protect the 
compressor from overheating. The cryogenic system was placed in the vacuum chamber to 
reduce the heat flux from surroundings. The recuperative heat exchanger was done as counter 
flow double pipe heat exchanger. To throttle the gas the linear valve made by Velan with the Cv 
coefficient 0.5 was used. All the components in the cryogenic system was insulated by the MLI 
(Multi Layer Insulation). All the temperatures were measured with the PT-100 thermometers. 
The measurements of the pressure were done by analogous manometers and pressure transducers. 
The design of the evaporator (double pipe heat exchanger) allows condensation of the different 
gases. However in this experiment, to generate the cooling power the heater made by resistant 
wire was wound on the evaporator.

![Diagram](image)

**Figure 3.** The scheme of the test stand with the measurement point.

### 3.2. Results

The investigations were focused on reaching the temperature below 100 K and producing the 
cooling power. The design capacity of the cooler is around 50 W in temperature 100 K. Based 
on the mixture optimization, mixture 1 was selected to the experiment due to the smallest 
amount of gases and relatively high efficiency. The cooler was fed with the gas mixture nr 1. 
The results of the measurements are given in Fig. 4. At the beginning of the measurement the 
discharge pressure rose to 25 bar. Due to the valve regulation, the fluctuations of the discharge 
and suction pressure occurred for the first 30 minutes of the measurement. The discharge 
temperature did not exceed 390 K. After 230 minutes the temperatures have stabilized. The 
minimum temperature was reached behind the J-T valve (T5) and was 94.1 K. The temperature 
before J-T valve (T4) was 117.9 K, the discharge temperature (T2) was oscillated around 380 K 
and the temperature of compressor oil in the sump (TIII) stabilized at 329 K. The discharge 
and suction pressure was 19.2 bar and 1.2 bar respectively. The values were obtained without 
cooling power generation. After 230 minute, the electric heater was turned on and the 50 W 
of cooling power was generated. The temperatures in the cryogenic section started to rise and 
stabilized after 10 minutes and stayed at 101 K behind J-T valve (T5), 120 K behind evaporator 
(T6) and 131 K before J-T valve (T4). The discharge pressure rose slightly from 19.2 bar to 19.9 
bar due to evaporation of the gases and the increase of gas volume. The rest of the parameters 
remained unchanged.

The power consumption ($\dot{P}$) during the generating the 50 W of cooling power ($\dot{Q}$) was 3.2 kW. 
Hence, the efficiency of the cooler is: $COP = \frac{\dot{Q}}{\dot{P}} = \frac{0.05}{3.2} = 0.015$. In reference with the Carnot
cycle ($\eta_c$), which equals 0.51 for the low and high temperature 100 K and 300 K respectively, the efficiency of the cooler is $\eta C = \frac{COP}{\eta_c} = 0.029$.

The net capacity can be calculated as $q_{net} = \frac{Q}{\dot{m}}$. Knowing the volume capacity of the compressor which is $\dot{V} = 23.63 m^3/h$, the density of the mixture at the compressor inlet $\rho = 1.24 kg/m^3$ and estimating the volumetric efficiency of the compressor as $\eta_v = 0.91$, the mass stream of the mixture is $\dot{m} = \eta_v \cdot \rho \cdot \dot{V} = 27.1 kg/h$. Knowing that, the net capacity is $q_{net} = \frac{Q}{\dot{m}} = \frac{50 W}{27.1 kg/h} = 1.86 kJ/kg$. The net capacity in comparison with the gross capacity is 12.3%. It means that the rest of the potential capacity is lost due to the irreversibility of the processes, heat leaks and pressure drops. However, reaching required temperature with one stage system and generating the cooling power is proven. Moreover, received data may be helpful in the cooler design optimization to increase the efficiency.

4. Conclusions
The J-T cooler fed with the gas mixture can be used to build the BOG re-liquefaction system. Presented results have confirmed that the require temperature to liquefy the methane at ambient conditions (111K) is possible to reach. Moreover, the optimization algorithm of the working fluid with the $\Delta h_{T_{min}}$ criteria was presented. The gross capacity of the optimal mixtures is around 60 kJ/kg. The cooling power of the tested cooler is 50 W in temperature around 100 K.

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