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Overview of the liquid natural gas (LNG) regasification technologies with the special focus on the Prof. Szargut's impact

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ABSTRACT

In the paper the overview of available technologies for Liquefied Natural Gas regasification is presented. Special emphasis is put on the Prof. Szargut's input to the topic. Both existing and theoretical solutions are shown. Additionally, the zero-order mathematical of on og the technologies is presented.

1. Introduction

Liquefied Natural Gas (LNG) is transported by the sea-ships with relatively low pressure (0.13–0.14 MPa) and very low temperature (about 100 K) in cryo-containers. Before further utilization it is compressed and then regasified. After that it can be directed to high pressure gas pipelines. Mentioned operations usually take place on the on-shore LNG terminals or on the local distribution stations. The LNG is transported to the local stations by means of tank trucks. Of course, the amounts the regasified gas in the on-shore terminal and in the local stations can not be compared - they are of different scale.

Liquid phase, as far as low temperature of the medium is connected with its high exergy. LNG receives this exergy during the liquefaction and is related with energy consumption in this process. The amount of the exergy was estimated by prof. Szargut [1]. The 3 MPa isobar of evaporating methane is shown in Fig. 1. According to the characteristic points shown in this Figure, LNG exergy can be computed as:

$$b_T = T_0(s_0 - s_B) - (h_0 - h_B) \tag{1}$$

where T is temperature and h stands for specific enthalpy. Enthalpy h_B results from the pumping work and can evaluated as:

$$h_B = h_A + \frac{1}{\eta_p} v_A (p_B - p_A) \tag{2}$$

where η_p stands for the overall pump efficiency and v_A is the specific volume of the liquid.

The entropy s_B results from the irreversibility in the pump:

$$s_B = s_A + \frac{q_f}{T_A} = s_a + (h_B - h_A)\left(1 - \eta_p\right)\frac{1}{T_A} \tag{3}$$

q_f is the friction heat released during pumping.

It can be easily estimated, that assuming presented above values of parameters of regasified gas, the thermal exergy of LNG is equal to 6.8 kJ/kmol.

When the LNG is evaporated in atmospheric regasifiers (what takes place in many on-shore terminals as well as in local regasifier stations) the cryogenic exergy is totally lost. What's more, in many cases, atmospheric regasifiers are thermally supported by gas combustion which additional increases the cost of evaporation. But there are also a lot of installations dedicated for exergy recovery during LNG regasification. They are mainly used for the production of electricity, but there are also rare examples of utilization of the LNG cryogenic exergy for other tasks, for example it is utilized in the fruit lyophilization process.

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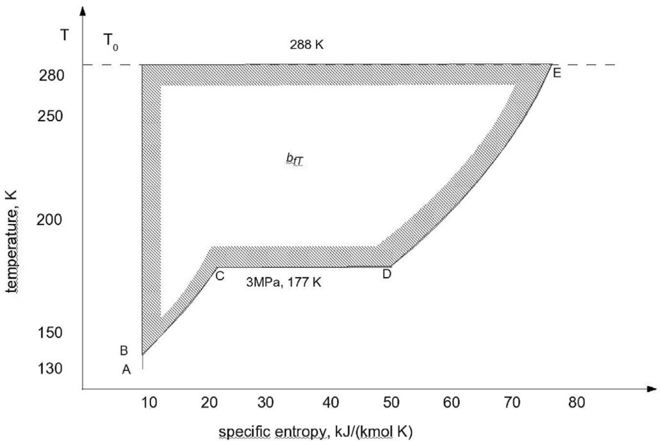

Fig. 1. Cryogenic exergy of LNG.

2. The cryogenic exergy recovery technologies

Available technologies for LNG cryogenic exergy recovery can be divided according to the principle of operation:

- direct expansion of LNG (open Rankine cycle, DEX) [2],
- Rankine cycles (RC) [3–7],
- Brayton cycles (BC) [9–20],
- combined cycles (CC) [21–29],
- Stirling cycle [30].

2.1. Direct expansion (DEX)

Direct expansion is very simple open cycle. LNG is pumped to the high pressure (about 27 MPa), regasified and then expanded in the gas turbine to the gas-pipeline pressure. Exergetic efficiency of this construction is relatively low - about 11%, but it is commercially utilized in a number of Japanese LNG terminals: Nigita 5600 kW, Higasi Ougishima (terminal 1) 3300 kW, Higasi Ougishima (terminal 2) 8800 kW; Himeji 1500 kW [2]. The scheme of open Rankine cycle is shown in Fig. 2. It is worth to mention, that DEX can be combined with Rankine cycles or Brayton cycle, which will result in exergy efficiency increment.

2.2. Open Rankine cycle with isochoric evaporation

This is interesting modification of DEX system. Namely, instead og liquid punk the isochoric evaporator is installed. It significantly reduces the investment costs, but it can only work in periodic mode. To assure fluency of work, two or more isochoric evaporators should be employed. The heat for evaporation can be taken from environment, or from the closed Rankine or Brayton cycle. The schematic diagram of this solution is presented in Fig. 3.

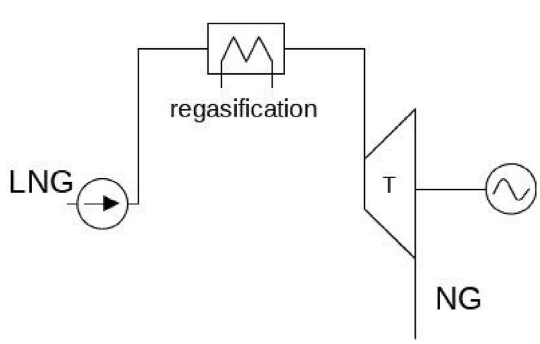

Fig. 2. Open Rankine cycle (adapted from Ref. [2]).

2.3. Rankine cycles

The very basic Rankine cycle is shown in Fig. 4. The main advantage of this solution is simplicity. It gathers heat from environment (for example from the sea water) and rejects heat to the evaporating engine in the condenser. So this is a case of so-called *cold engine*. Exergetic efficiency of this solution is not too hight and places on the level of 20%. But, what was mentioned, the main advantage of this solution is simplicity.

High temperature heat source is usually environment or sea water - what is especially attractive in on-shore terminals. The exergetic efficiency can be increased, if instead of sea water higher temperature heat source is used. It can be technological waste heat (if any) or solar energy. But it of coarse increases the investment costs.

In Table 1 the list of installed Japanese Rankine and open Rankine systems is presented [2].

The efficiency of the Rankine cycle can be easily increased by the installation of additional heat exchangers: heater and regenerator. With the heat sources temperatures equal to 500 °C and −50 °C the efficiency can obtain up to 52% [18]. The schematic diagram of modified cycle is shown in Fig. 5. As it can be noticed, in the presented Rankine cycles (Figs. 4 and 5) only the exergy resulting from

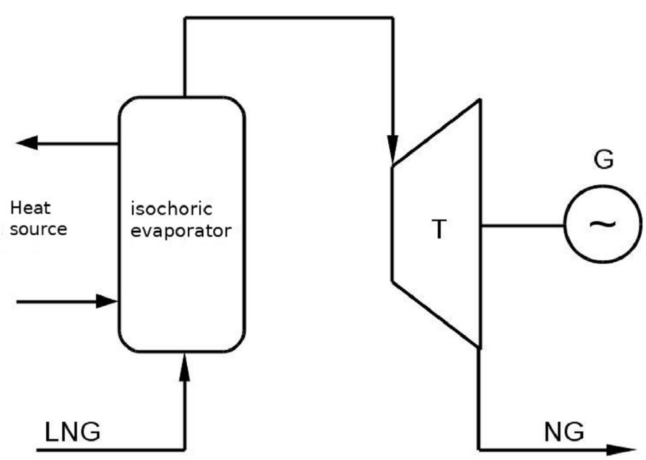

Fig. 3. Open Rankine cycle with isochoric evaporator.

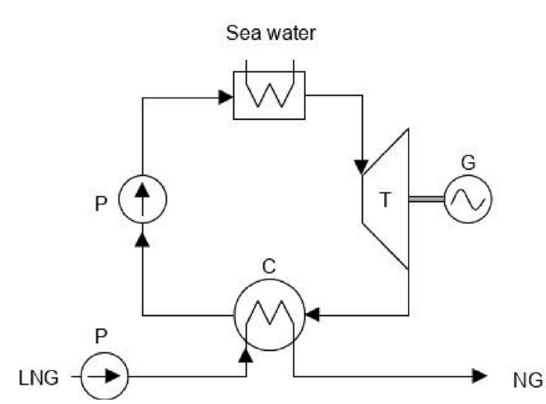

Fig. 4. Cryogenic Rankine cycle (adapted from Ref. [2]).