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COMBINED HEAT AND POWER SYSTEMS IN LIQUEFIED NATURAL GAS (LNG) REGASIFICATION PROCESSES

1. INTRODUCTION

Liquefied natural gas (LNG) is produced in the process of natural gas liquefaction taking place in the neighborhood of natural gas deposits. The gas at close-to-ambient pressure is transported by methane ships, then is unloaded on land or pumped to insulated floating storages. A typical terminal LNG regasification consists of a few subsystems, i.e. ship unloading system, LNG storage system, low-pressure LNG pumping system, compression system for vaporized reservoir gas, reliquefaction system, high-pressure pumping and regasification system. Regular BOG produced while unloading LNG from the ship and during routine operations is reliquefied under the influence of mixing with cooled LNG. Liquefied gas is then transported by high-pressure pumps at the pipeline pressure and heated by LNG vaporizers to a temperature of about 20°C. Afterwards the gas may be directed to further transport or introduced to the distribution network [6, 8].

The regasification of LNG is a very energy-consuming process. The heating of 1.4 mln m^3/h of gas from a temperature of -160°C to 20°C at a pressure of 8.25 MPa requires about 220 MW. Moreover, half of the presently applied regasification systems employ the open rack vaporizers (ORV) for heating up the LNG, with marine water as a heat carrier. In the case of terminals located in cold climate zones, the submerged combustion vaporizers (SCV) have to be used [4,5].

Other LNG regasification methods can be also applied, e.g. ambient air vaporizers (AAV), heaters or waste heat from cooling towers making use of such heat exchange fluid carriers, e.g. ethylene glycol, propylene glycol or methanol. The use of Rankine cycle is another innovative solution.

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A plot of temperature vs. enthalpy for LNG having an exemplary mole composition (%): 91% methane, 8% ethane, 1% nitrogen is presented in Fig. 1. At a pressure of 3MPa LNG is a mixture, which in a supercritical state remains liquid till the moment the boiling point is reached; then it starts evaporating at a constant temperature and in a gaseous state is heated up to the pipeline temperature. Supercritical conditions are observed for LNG mixture at a pressure of 10 MPa. The transformation from the liquid to the gaseous state has a steady course with the increasing temperature and without determined boiling point. It can be further observed that the differences in temperature profiles may affect the selection of the thermodynamic process for power generation.

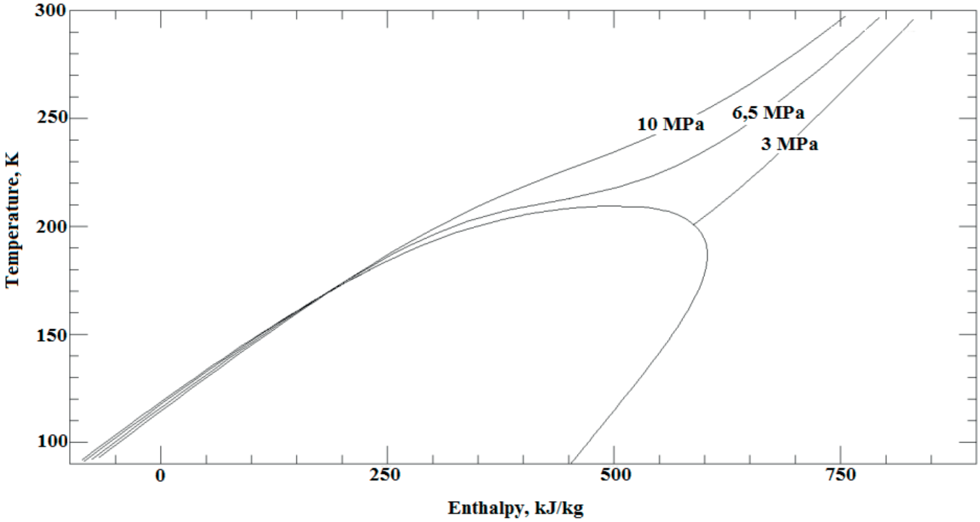

Fig. 1. LNG temperature vs. enthalpy. Upper and middle curves refer to a constant pressure of 10 MPa and 6.5 MPa (supercritical conditions), respectively; lower curve stands for a subcritical change of state at 3MPa. Own study [9]

2. RANKINE CYCLE FOR HEAT TRANSPORT

In an ideal subcritical Rankine cycle (regardless the working agent) the fluid is compressed, then is heated in constant pressure conditions and decompressed in an isentropic process. Then the fluid is condensed at constant temperature and pressure to the original state and the operation is repeated.

Power (electrical energy) can be produced with the use of LNG as cold radiator in the classic Rankine cycle as shown in fig. 2. LNG has been applied for condensing working agent which circulated in the closed system, as in the case of steam power plants based on this solution. The ideal efficiency of Rankine (or Carnot) cycle can be defined in the following way:

$$\eta = \frac{T_2 - T_1}{T_2}$$

where:

T_2 – temperature of heat source [K],

T_1 – absolute temperature of radiator [K].

When applying LNG as a radiator (T_1), the temperature difference (T_2 - T_1) increases, making power generation more efficient. Power generation is proportional to the difference of temperatures at a constant temperature of heat source. The selected working fluid must be stable in the high temperature conditions and condense at lower temperatures without creating the freezing problem.

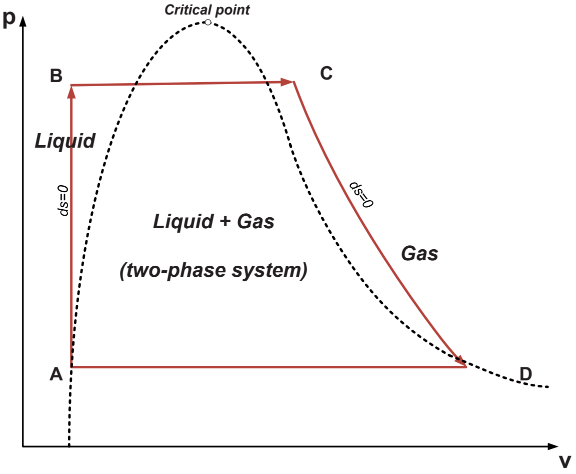

Fig. 2. Rankine cycle in the p–v system

The Rankine cycle consists of isentropic compression of working agent, which is then heated up under a constant pressure [7]. Then follow decompression, isobaric cooling and condensation of the working fluid (Fig. 2.). In the cycle presented in fig. 3, the working fluid is pumped to the supercritical pressure value, i.e. usually ca. 10.3 MPa. Fluids under high pressure is pre-heated in the exchanger-regenerator, then in a heater to about 300°C. Heat may come from heaters or waste heat from the gas turbine generator. Vapors at high temperature and in the supercritical state are then decompressed to the atmospheric air value in an expander. In this way power is generated. Low-pressure vapor is cooled down in the regenerator’s exchanger and condensed in a condenser. LNG is condensed in the condenser with the use of the heat of working fluid condensation heat.

For electrical energy generation purposes one can use such pure components as butane, propane and ethane playing the role of working fluids. The efficiency of power generation with the use of butane is low due to its high temperature of condensation. Butane undergoes condensation at a temperature of –1.1°C in the atmospheric pressure conditions. Thus, butane as a working fluid cannot be efficiently used for very low temperatures of LNG. Propane is a more efficient working fluid as it can be condensed at much lower temperatures, i.e. –42.2°C in the atmospheric pressure conditions.

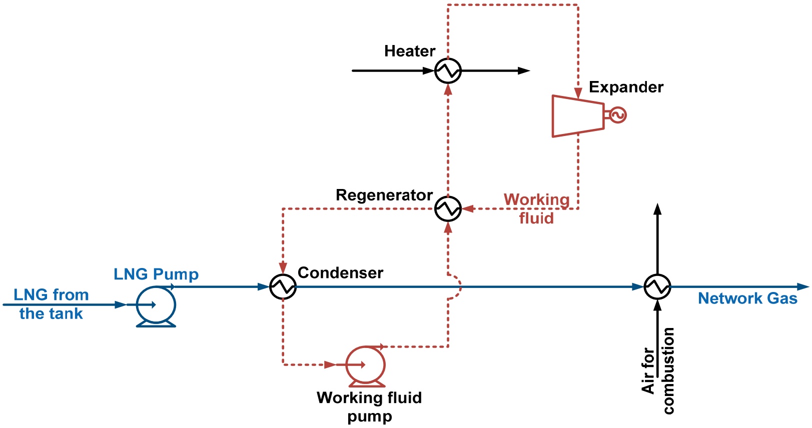

Fig. 3. Schematic of Rankine cycle for power generation, after [1]

The Rankine cycle (A→B→C→D) superimposed on the plots of temperature and changes of enthalpy of marine (sea water) heat source (b→a) as well as radiator consisting of an evaporation system for liquid methane in subcritical pressure conditions (1→2→3→4) is presented in fig. 3. The physical process for subcritical pressure conditions of 2.5 MPa is illustrated in fig. 4 and discussed in table 1. Methane at a pressure of 2.5 MPa and temperature of 174 K boils off.

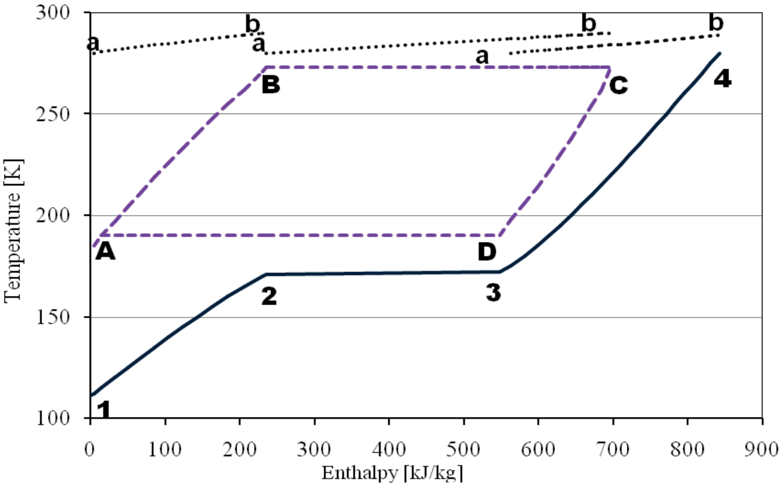

Fig. 4. Temperature vs. enthalpy for marine source of heat (a-b), Rankine cycle (dashed line) and regasification of liquidated methane (continuous line) at a pressure of 2.5 MPa. Ethane as working fluid in the Rankine cycle. Own study based on [2]

Table 1

Thermodynamic properties for points of state presented in fig. 4. Own study based on [1]

Processes	Points of state	Temperature [K]	Enthalpy changes [kJ/kg]
Cooling of heat source (sea water)	b → a	290 – 280	840
Heating of liquid ethane	A → B	190 – 275	235
Evaporation of ethane	B → C	275	460
Expansion of ethane vapor	C→ D	275 – 190	150
Condensation of ethane vapor	D→ A	190	545
Heating of liquid methane	1 → 2	111 – 172	235
Evaporation (regasification) of methane	2 → 3	172	310
Heating of methane vapor	3 → 4	172 – 280	295

The course of LNG evaporation changes with the change of LNG composition. An exemplary course of temperature changes in a function of enthalpy for subcritical pressure of 2.5 MPa is presented in fig. 5. Higher ethane content in LNG results in the increase of temperature, in which LNG boils off, and faster temperature growth depending on the enthalpy, which may have a negative effect on the use of ethane as a working fluid in the Rankine cycle.

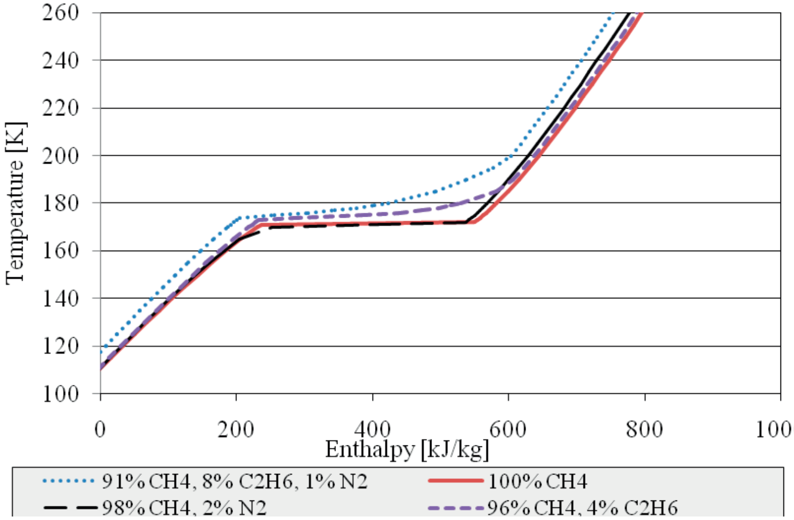

Fig. 5. Evaporation of pure methane and mixture of methane, ethane and nitrogen under a pressure of 2.5 MPa. Own study [9]

According to the thermodynamics fundamentals a classic thermal engine requires a source of heat and a radiator of various temperatures. The key to the understanding of proposed LNG evaporation processes is the fact that the temperature difference in heat sources (b→a) and radiator fed by liquid methane (1→4) suffices to run the Rankine or Brayton cycle. The temperature/enthalpy profiles in the Rankine cycle and methane evaporation process are similar therefore can be connected. With the properly selected working fluid in the Rankine cycle one can calculate the cycle parameters, including relative velocities of various working fluids and power generation [7]. The use of ethane is problematic as it has low boiling point and is not fit for LNG evaporation (the condensation temperature is too low to heat LNG to the required pipeline temperature). In this case the rejected heat in the ethane condenser goes to liquid methane and may produce up to 85% of total heat needed for LNG evaporation. The direct heat transfer is a source of heat energy (over condensation temperature of ethane) without transient heat transport (e.g. brine).

In practice, in the conditions of subcritical methane pressure the temperature can be used in the process of boiling and condensation. In the supercritical pressures conditions steam should be extracted between two or more turbine states to make a better use of the heat passing through the system.

Not all LNG regasification plants can adjust the loads of evaporated LNG to the demand for power if integrated systems are concerned. Situation deteriorates when varying requirements regarding generated electrical energy must depend on higher inertia of the heat turbine. This limitation and the lack of fitting of temperature vs. enthalpy relation may in some cases show to the necessity of solving this problem as an alternative of the Rankine cycle. Brayton cycle may be another alternative.

The Brayton cycle is fed with the relatively high–temperature source of heat, i.e. combustion system. The closed Brayton cycle may cooperate with the dry combustion system with the use of, e.g. nitrogen as the working fluid, obtaining very high heat use coefficient or as submerged combustion systems with working fluid, usually used in gas-fed evaporation systems.

Due to the high thermal efficiency, the multicomponent working fluids are usually used for LNG condensation. The same principle can be applied for power generation cycles, where LNG plays the role of a radiator. Multicomponent fluids undergo condensation in varying temperature conditions and their compositions can be so selected as to fit them to the LNG evaporation plot [3]. In the presently applied plate or spiral exchangers, approaching very close temperatures is most economic. The shape of the working fluid condensation curve can be accurately fitted by adjusting the mixture's composition and by making its curve parallel to the LNG evaporation curve. In this way the periodical temperature changes typical of the single component system can be avoided.

For each LNG composition there exists an optimum composition of mixed fluid. An exemplary composition of mixed working fluid and the corresponding LNG composition are presented in Table 2.

For the sake of comparison of thermodynamic capacities of various working fluids the LNG evaporation curve was graphically visualized against condensation plots and presented in Fig. 6 [1]. Because of their higher condensation temperatures, butane and propane have to be heated at the inlet to the condenser to avoid periodical changes of temperature in the condenser. On the other hand, the mixed fluid at the condenser inlet stays in the zone of two phases avoiding periodical temperature changes. The composition of mixed fluid can be so adjusted that the condensation takes place at a temperature close to LNG, which finally results in a higher capacity of the power generation cycle.

Table 2

Exemplary composition of LNG and mixed working fluid

Molar concentration %	*LNG*	*Mixed working fluid*
C_1	*91*	*17*
C_2	*5*	*26*
C_3	*3*	*34*
C_4	*1*	*23*

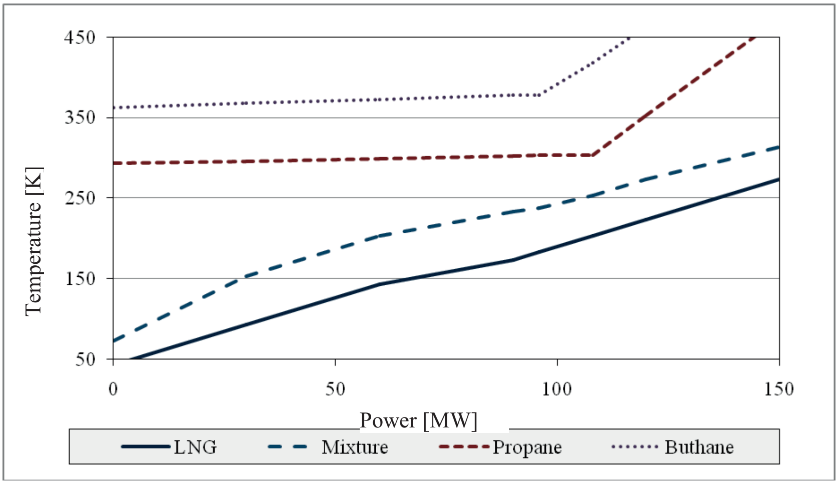

Fig. 6. LNG regasification curve (lower) and condensation of working fluid. After [1]

3. CONCLUSIONS

The reliability and availability of sufficient amounts of waste heat from a gas turbine for LNG regasification is of top importance to the co-generation plants. Production usually differs from demands, causing fluctuations of available waste heat. On the other hand, waste heat is constantly applied for LNG regasification in the basic production. For this reason the reserve heat sources are frequently used.

The traditional LNG regasification requires about 1.8 mln m^3/d of sea water or about 230 MW of gaseous fuel at the yield of about 33.6 mln m^3/d of gas. These requirements are not valid in integrated production plants thanks to the mixture evaporation in Rankine cycle as a source of heat. For the above values, the Rankine mixed fluid cycle produced about 110 MW and part of this power can be used for the needs of the plant.

In the integrated plant based on the Rankine cycle the capacity of turbine increases on average by 35%.

Fuel gas demanded by integrated-production plants covers the consumption of about 520 MW, mainly due to the considerably higher productivity, which certainly exceeds the yield in the fuel gas consumption in the ORV system. As compared to the SCV system, the co-generation plants consume much less gaseous fuel, simultaneously producing much more power.

The output of a plant should be compared with its power generation capacity. The entire production of integrated system is much bigger than in traditional LNG regasification installations.

New and newly designed on- and off-shore LNG reception terminals should be adjusted to the constantly changing environmental, legal and technological restrictions. The cost of exploitation of regasification objects is evaluated on the competitive LNG market. The „thermal" integration of a power plant making use of Rankine or combined cycle is a natural process of LNG regasification technology development, which can lower the total cost of installation and increase the total thermal capacity.

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