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Performance analysis of small-scale power cycles for LNG physical exergy recovery

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Abstract. Stricter air pollution regulations and emission controls have made the liquefied natural gas (LNG) a promising alternative fuel for marine transportation. LNG as a cryogenic fluid has large physical exergy (about 1000 kJ/kg), that can be partially recovered during regasification process in fuel systems of LNG-fuelled vessels. One of the ways of utilizing LNG physical exergy is to use evaporating LNG as a low-temperature heat sink to produce electric power in thermodynamic cycles, such as Organic Rankine Cycle (ORC). The efficiencies of major components of ORC systems, such as expanders or cryogenic pumps, depends largely on the power rating of the system, influencing the optimal parameters of the planned cycle. This research consists of performance analysis and thermodynamic optimization of the thermodynamic cycles for LNG exergy recovery in small-scale transportation systems.

1. Introduction

In recent years, accelerated consumption of fossil fuels, and related to them environmental problems such as global warming, ozone layer destruction and atmospheric pollution were the reason for introducing air pollution regulations and emission controls. One way to deal with this situation is to change fuel for Natural Gas (NG), as it is the fossil fuel with the lowest carbon footprint and the cleanest combustion [1, 2]. The most feasible way to transport and store natural gas is in its liquefied form (LNG). LNG should be evaporated before feeding into the combustion chamber, providing latent heat. It can lead to the loss of stored exergy of natural gas.

2. ORC cycle for LNG exergy recovery

2.1. Cycle description

One of the possibilities to improve the economics of LNG evaporation is to use the evaporator as the heat sink in the Organic Rankine Cycle (ORC). Figure 1 shows the scheme diagram of the analysed ORC system for LNG physical exergy recovery. LNG is evaporated and heated up (I-II) in heat exchanger (that is also the ORC condenser) and later warmed up to ambient temperature in heater (II-III) to be fed to the engine. Working fluid vapour from expander outlet is condensed in heat exchanger (1-2) and pressurized in pump (2-3). Then it is evaporated and heated (3-4) using ambient as a heat source. Finally, it is expanded (4-1) to generate mechanical work.

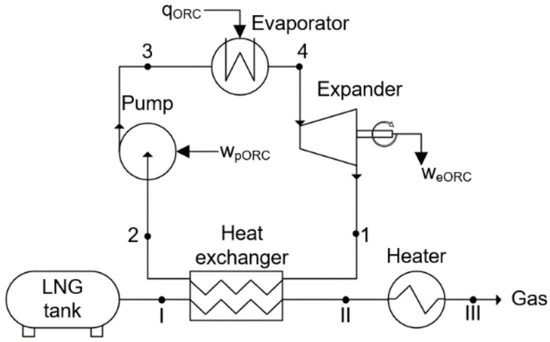

Figure 1. Scheme diagram of analysed ORC system.

The use of ORC circuits in the LNG evaporation process is not a new idea. Organic Rankine cycles for the recovery of low-temperature cryogenic gas exergy have been used in industry since the late 1970s. However, such devices have so far been built in general at large regasification installations for liquefied natural gas (Japan, Spain, France) [3]. Research is currently underway to use such circuits on a smaller scale that can be used for example to feed gas engines in marine transportation vessels or even smaller units. They are widely analysed in the literature in various variants and for various applications [4-7]. However, such research focuses only on the thermodynamic efficiency analysis of the ORC cycle along with the change of scale. With this type of consideration, not only the scale effect on process efficiency should be taken into account, but also on the efficiency and availability of system components such as pumps or expanders.

2.2. Process modelling and assumptions

Model parameters are listed in table 1.

Table 1. Working parameters of the analysed system.

Parameter	Value
LNG pressure (p_I)	6 bar
Minimal condenser pressure (p_1)	1 bar
Temperature at evaporator outlet (T_4)	283 K
Pump and turbine efficiencies	based on [8]

It was assumed that the LNG fuel system analysed is a low-pressure one, therefore pressure in the LNG line was assumed to be 6 bar. The heat source temperature was assumed to be 283 K. To avoid under-pressure in the ORC system, the minimal pressure was assumed to be 1 bar. Moreover, the authors assumed that the liquid fraction does not occur in the expanders and there is no pressure drop in the heat exchangers. Pressure at the pump outlet (p_3) was a variable.

Landelle et al. [8] have shown that the efficiency of the major components of ORC systems drops significantly for the low-scale systems. Based on the empirical data, the authors obtained the formulas for pump and expander efficiencies as functions of pump and expander power, assuming the logarithmical growth of efficiency with increasing scale.

Thermodynamic simulation of the considered system was performed using Python code developed by the authors. Thermal properties were calculated using the open-source CoolProp library [9]. The calculations were performed with the iterative method: at first pump and expander power are calculated (the initial component efficiencies are assumed). Efficiencies of pump and expander are then calculated for the system powers and another iteration is performed with new efficiency values. Iterations are continued until the convergence criterium is achieved for both pump and turbine efficiencies:

$$\frac{|\eta_{\text{exp}} - \eta_{\text{ exp\_previous}}|}{\eta_{\text{exp}}} < 0.01 \quad (1)$$

$$\frac{|\eta_{\text{pump}} - \eta_{\text{ pump\_previous}}|}{\eta_{\text{pump}}} < 0.01 \quad (2)$$

where: η_{exp}, η_{pump} – expander and pump efficiencies from current iteration; $\eta_{exp\_previous}$, $\eta_{pump\_previous}$ – expander and pump efficiencies from previous iteration.

Exergy efficiency was calculated as a ratio of net work (w_{net}) to exergy input (e_{in}) [10]:

$$\eta_{exergy} = \frac{w_{net}}{e_{in}} \quad (3)$$

In case of analysed ORC system equation (3) becomes:

$$\eta_{exergy} = \frac{P_{exp} - P_{pump}}{\dot{m}_{LNG} \cdot e_{LNG}} \quad (4)$$

where: P_{exp} and P_{pump} – expander and pump power, $\dot{m}_{LNG}$ – LNG mass flow, e_{LNG} – physical exergy of LNG at the inlet of the heat exchanger.

2.3. *Working fluid selection*

Recalling the assumptions given in the previous section, four low-temperature ORC working fluids have been chosen and listed in table 2. Low freezing point is the most crucial characteristic of the working fluid. As the condensation pressures were assumed to be higher than atmospheric pressure, another very important factor is normal boiling temperature. The boiling temperature of working fluid should be as close as possible to the temperature of LNG in the condenser, in order to maintain a large difference between evaporation and condensation temperatures.

For all of the analysed fluids, the ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) were analysed. For all fluids, ODP is equal to 0. The GWP factor for the hydrocarbons is relatively low, while for HFC-23 and PFC-14, it is much higher.

Table 2. ORC working fluids and their characteristic parameters.

Working Fluid	$T_{Boiling}$ (K)	$p_{Critical}$ (bar)	$T_{Critical}$ (K)	$T_{Solidification}$ (K)	GWP	ODP
Ethane	184.6	49	305.3	101	5.5	0
Ethylene	169.5	50.6	282.5	104	3.7	0
HFC-23	191.1	48.2	299.3	118	14 800	0
PFC-14	145.3	37.5	277.5	89.5	7 390	0

3. Results

Calculations were performed for 4 selected power ratings of natural gas fuelled engines: 200 kW, 1 MW, 2 MW, 12 MW, which corresponds to typical power ratings of trucks, locomotives, small and large marine vessels engines respectively. The natural gas flow rate for selected engines vary between 65 and 3700 m^3 / h at standard conditions. Results are shown in figure 2.

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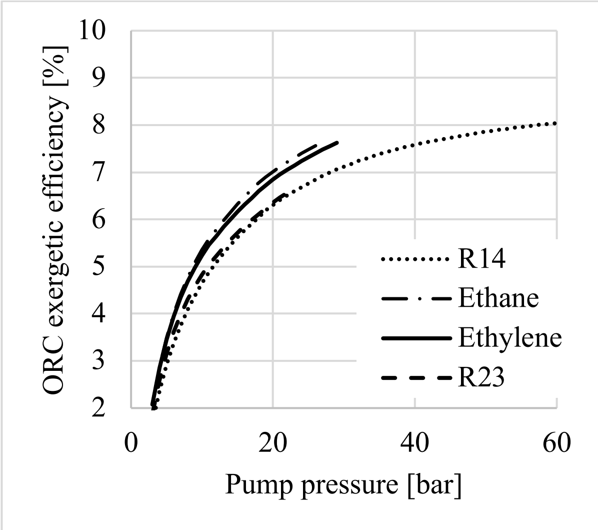
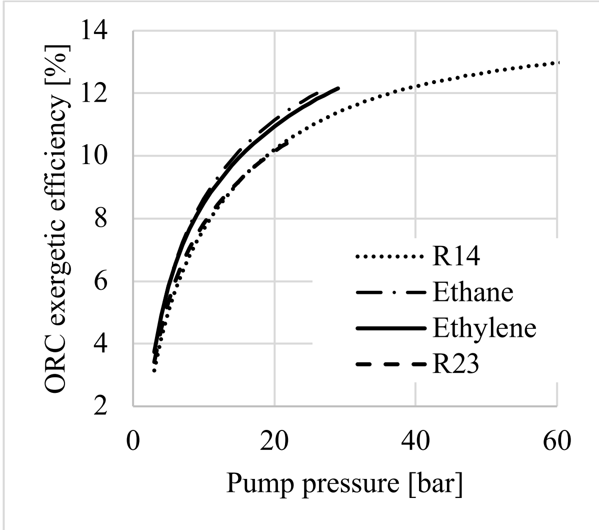


a)



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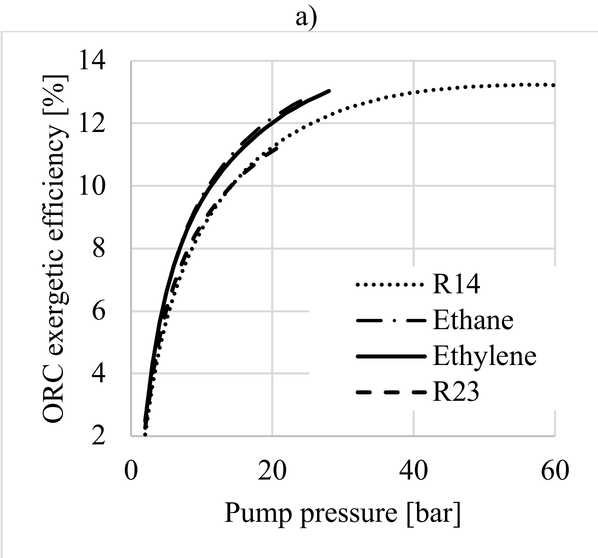

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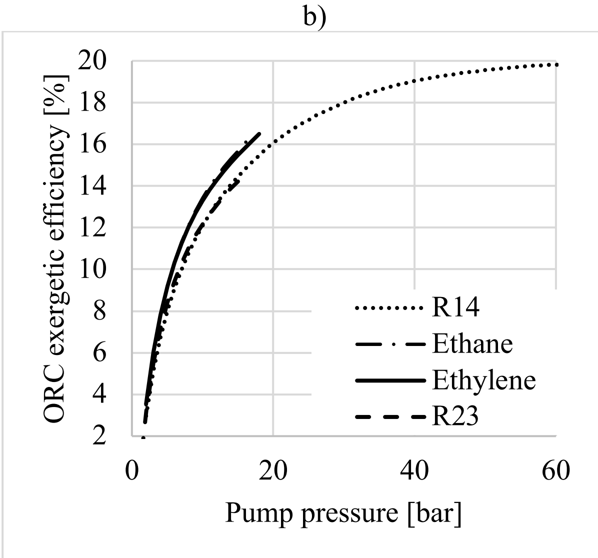

d)

Figure 2. Calculated ORC efficiency for different power ratings:
a) 200 kW, b) 1 MW, c) 2 MW, d) 12 MW

Achieved exergy efficiencies (shown in figures above) depend on the pump pressure of working fluid in a liquid state. The simulation was performed until the liquid fraction occurred in the expander, in case of 3 working fluids (ethane, ethylene and R23), the liquid phase was present in the expander at pump pressure about 20 bar, in case of the R14 liquid fraction was present for pressure above 100 bar.

As a result of the performed simulation, it can be seen that maximum efficiency drops significantly as the LNG regasification system capacity decreases. The main reason for that is the decrease in pump and expander efficiencies with the scale of the system.

It can be also seen that there is no need for increasing high pressure in ORC cycle above 30 bar in small systems. In the case of R14 as a working fluid, higher pressures are possible to achieve but the increase of exergetic efficiency is not significant. Only in case of large-scale systems (large marine vessels) increasing of R14-based cycle pump pressure may lead to significant increase of exergy efficiency.

Where it comes to the working fluid selection, the differences in cycle efficiencies for pump pressures below 20 bar are small. The highest efficiencies are achieved for ethane and ethylene. These two fluids are also most environmentally friendly (see table 2).

Performed simulation indicates, that the achievable exergetic efficiencies of LNG exergy recovery systems based on ORC cycles are as follows:
- for road vehicles: 7%
- for railway transport: 12 %
- for small marine vessels: 13%
- for large marine vessels: 16% (ethane/ethylene @20bar) or 20% (R14 for pressures above 60 bar)

4. Conclusions
Natural gas in liquefied form, before delivery to engines, should be evaporated and warmed up to ambient temperature. During this process, it is possible to recover some of the energy previously incurred for its condensation. The LNG exergy recovery system using ORC is a well-known and widely used in existing regasification units, but this applies only to stationary facilities with very high capacity and thus the high efficiency of the ORC. In medium and low capacity systems the efficiency of the ORC is significantly lower. Calculation shows, that in mobile applications, LNG exergy recovery ORC based systems may be used only with engines of large natural gas demand (i.e. large marine vessels). In other cases, use of the ORC exergy recovery system may not be justified due to not sufficient efficiency and a significant complexity. For small-scale mobile units, a more appropriate exergy recovery system should be found.

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