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Cryogenic ORC To Enhance The Efficiency Of LNG Regasification Terminals

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Abstract

This paper focuses on the design and the optimization of Organic Rankine Cycle (ORC) for LNG regasification plants. This technology is a promising solution with large benefits attainable in terms of primary energy savings compared to both Open Rack Vaporizer (ORV) and Submerged Combustion Vaporizer (SCV) technologies. Different cycle configurations are investigated including the option of multilevel condensation plants. The adoption of several working fluid candidates is analyzed and different design constraints are included to obtain a more reliable solution. The optimal combinations of cycle configuration and working fluid are presented with a preliminary design of the main components. Finally a dependency study on the seawater temperature is carried out.

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Keywords: LNG regasification, cold exergy, cryogenic ORC, energy efficiency

1. Introduction

LNG Regasification is the final step of the "LNG value chain" that starts from upstream facilities (on and/or off-shore field development and associated pipelines), goes through Liquefaction Plants and is delivered to LNG import

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Terminals via shipping (LNG transport). Liquefied Natural Gas (LNG) is transported worldwide by ship in cryogenic vessels where it is stored at ambient pressure and at temperature of -160°C. LNG is pumped at high pressure, then vaporized and delivered to gas pipelines for distribution. Several technologies for LNG regasification are available on the market; among them, the most important are the Open Rack Vaporizer (ORV), the Submerged Combustion Vaporizer (SCV) and the Intermediate Fluid Vaporizer (IFV) [1]. In the first, LNG flows upwards in tubes while seawater flows outside in counter flow. This technology is widely used because of its low operational costs, but it is a capital intensive solution because of the large heat transfer surfaces and the need for water treatment. In addition, it may turn critical because of vibrational issues in part load. The second regasification technology comprises a pool of water heated by the flue gases from the combustion of a fraction of the regasified gas. While this technology is compact, it entails a high consumption of primary energy. Finally, the IFV consists of a shell and tube heat exchanger in which an intermediate fluid vaporizes by absorbing heat from the seawater and condenses by releasing heat to the LNG. All these technologies involve the consumption of electrical energy and/or fuel.

One of the most promising options to increase regasification plant efficiency is the introduction of a power cycle working between the seawater and the vaporizing LNG. This is an interesting solution from both a theoretical (LNG is a unique industrial-scale example of “cold exergy”) and technological (a non-conventional design of each component must be addressed to face difficulties related to cryogenic temperatures) perspective. ORC are the most reliable option for this field thanks to the possibility they provide to reach cryogenic temperatures while avoiding vacuum condition in the condenser. They have been studied for this application since 1980 and some pilot plants have been installed in Japan [2, 3]: unfortunately, very little data is available for these installations where propane, R13, R22 and R23 were used as working fluid and the cycle was a single level cycle. Power output for these plants ranges between 130 kW and 5 MW. In the literature, a variety of recent studies are focused on the topic. Invernizzi and Iora [4] have studied various solutions to increase the efficiency of LNG regasification terminals with closed Brayton cycles, with ORC receiving heat from a low temperature heat source, or from seawater and with CO_2 closed cycles. As regards ORC, both simple and double condensation level cycles have been investigated with butane, propane and ethane as working fluid; in addition, the possibility of using propane/n-pentane mixtures is proposed.

Sung and Kim have investigated a dual loop ORC capable of recovering heat from a dual-fuel engine and vaporizing LNG [5]. Working fluids are selected among many candidates and final configuration works with n-pentane in the high temperature cycle and R125 to vaporize the natural gas. Kim et al. [6] have examined the use of binary mixture fluids in a complex three-stage cascade ORC configuration: R14/propane and ethane/n-pentane mixtures are the most appropriate for the first stage and second/third stage respectively. Similarly, other works deal with binary or ternary compound systems [7-10]. Recently ORMAT applied for a patent focused on the topic proposing several different cycle configurations [11].

The aim of this study is to evaluate the benefits attainable with the installation of an ORC plant as an alternative to ORV or SCV technologies. Respect to other works in literature a screening of several candidate working fluids is performed in both single and double condensation plant configurations highlighting the most promising solutions for the efficiency increase of LNG regasification plants.

Nomenclature and acronyms

η	efficiency
$\dot{m}$	mass flow rate, kg/s
W	power, kW
BOG	Boil Off Gas
GWP	Global Warming Potential
LHV	Lower Heating Value, MJ/kg
LNG	Liquid Natural Gas
IFV	Intermediate Fluid Vaporizer
ORC	Organic Rankine Cycle
ORV	Open Rack Vaporizer
SCV	Submerged Combustion Vaporizer
SFC	Specific Fuel Consumption, kg/tonn

2. Plant description

In a conventional regasification plant, LNG is pumped from the saturated liquid condition (atmospheric storage at -160°C) up to about 80 bar. Based on Saipem's experience†, a reference scenario with four parallel regasification lines has been considered. Each one vaporizes 38.6 kg/s of LNG up to a temperature of 3°C and requires a thermal load of 27.2 MW_{th}. Depending on the regasification technology the heat for the LNG vaporization can be provided by seawater (ORV), by fossil fuel combustion (SCV) or by organic fluid condensation (IFV and ORC). We assume a heavy LNG composition made up of 87% methane, 8% ethane, 3% propane plus traces of heavier hydrocarbons and nitrogen. Independent of the regasification technology, the plant requires electrical power to operate each regasification line LNG pumps (1500 kW) and the boil-off gas (BOG) compressor (345 kW). In addition, we consider about 9000 kW of fixed plant needs that include utilities, controls systems, lighting and building air conditioning etc. For ORV and ORC additional electrical power is required for the seawater pumps while the SCV technology needs an additional fuel consumption. We evaluate the line's primary energy needs in terms of specific equivalent fuel consumption, SFC, as:

$$SFC = \frac{\frac{W_{el}}{\eta_{el} LHV} + \dot{m}_{CH_4}}{\dot{m}_{LNG}}$$

Where η_{el} is the yearly average efficiency of the power plants connected to the national grid and LNG Lower Heating Value (LHV) is equal to 49 MJ/kg. W_{el} is the total electrical power consumption that can be calculated as respect to one single line (LNG pumps plus BOG compressor consumption) or for the entire plant (four regasification lines plus fixed needs). Plant SFC for ORV and SCV technologies is 5.77 kg_{CH4}/t_{LNG} and 18.23 kg_{CH4}/t_{LNG} respectively.

Figure 1 depicts the two ORC saturated plant configurations investigated, namely the single and the double level condensation cycle. In both configurations seawater is the sole heat source and LNG is vaporized mainly by the heat released by organic fluid condensation. An additional stream of seawater is used to complete the LNG vaporization.

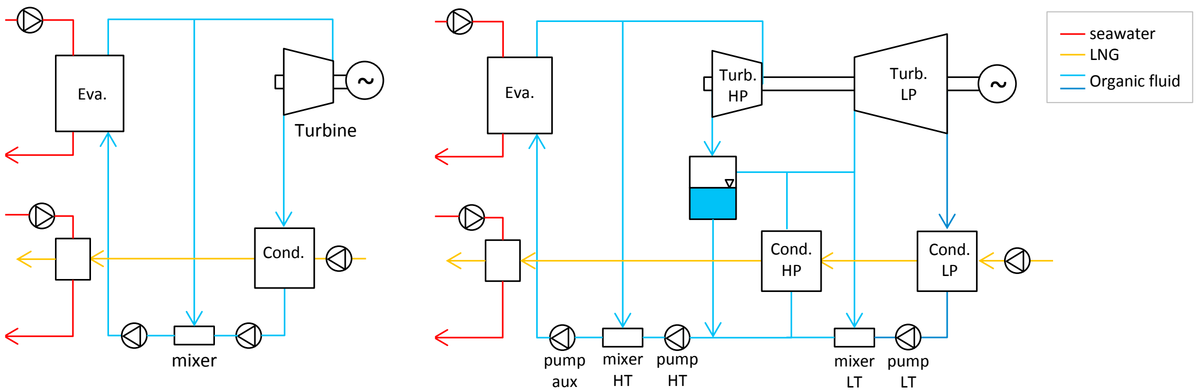

Figure1. Plant schemes of the studied configurations: (left) single condensation level cycle, (right) double condensation level cycle.

- Single condensation level cycle (Figure 1, left): this is the simplest cycle layout. It operates with a pure fluid in a single condensation level configuration. The capital cost is the lower of the two layouts and it easy

† SAIPEM is a proven world-class EPC Contractor in Oil&Gas Industry, for offshore, onshore and drilling Projects. Focusing on the subject of the present article Saipem has a well-established experience covering the entire LNG value chain, ranging from Onshore Liquefaction (EPC, FEED and bid phases of the Projects) to LNG Regasification (onshore and FSRUs – Floating Storage and Regasification Units), including LNG Tanks.

operation is ensured. One drawback is that the power production is considerably lower than the other solution with a lower reduction of the SFC.

- Double condensation level cycle (Figure 1, right): this works with a pure fluid and allows the achievement of a higher efficiency thanks to a lower irreversibility in the heat exchange occurring in the LNG regasification process. After the first expansion, the fluid is split into two streams: one condenses at high pressure while the other further expands and eventually condenses in a lower pressure condenser. A two phase separator is added to remove the liquid content before the low-pressure turbine admission and limit blade erosion. As suggested in ORMAT patent, preheating is realized by means of regenerative bleeding from the turbine inlet in order to avoid the risk of seawater icing on tube walls.

The evaporator and the condenser might be designed as shell and tube heat exchangers, after careful checking of the operating conditions to verify and assess heat exchanger type selection for the specific application: The evaporator consists of a bundle of seawater tubes submerged in a pool of evaporating organic fluid (like a kettle reboiler unit), while in the condenser the organic fluid vapours condense on a bundle of cold LNG tubes. Similar components are already used in IFV technology and the main concern regards the choice of material to withstand high pressure differences and cryogenic temperatures in the condenser. Pumps are expected to be multistage centrifugal pumps, while the expander can be arranged in either axial multistage (suitable for high volume ratio expansions) or centripetal inflow turbine configuration (common in low temperature applications and suitableto expand two phase fluids). Table 1 lists the common assumptions used for the ORC technology. In addition, we have assumed a nominal seawater temperature of 9°C.

Table 1. Assumptions for the ORC technology simulation.

ORC Turbine isentropic efficiency	80%		Turbine bleeding pressure drop	2%	
ORC pump hydraulic efficiency	75%		Evaporation temperature drop	1	°C
Mechanical-electric efficiency	95%		Condensation temperature drop	1	°C
Pinch point temperature difference	3	°C	mixer spray pressure drop	2	bar

A simulation framework has been developed in Excel+VBA environment and Refprop 9.1 [12] is used for the calculation of the working fluids thermodynamic properties. Each plant is optimized with respect to minimize the SFC of the system (which is strictly linked to the ORC power output) by varying the evaporation and the condensation temperatures of the ORC and considering four constraints in order to respect the technological limits of some components. These are as follows:

- Minimum vapour quality at the expander outlet is set to 0.1 with the aim of reducing blade erosion and to maximize the component efficiency
- Maximum isentropic volume ratio is set to 10 in order to obtain a good expansion efficiency with a radial inflow turbine or a multistage axial turbine with a limited number of stages.
- An additional limit of minimum temperature equal to -45°C can be considered in order to evaluate the performance of plants that do not require costly materials specifically developed for low temperature conditions.

The nonlinear optimization algorithm uses the Generalized Reduced Gradient code, which was developed by Leon Lasdon et al. [13] and enhanced by Frontline Systems, Inc.

Eleven working fluids are selected from among hydrocarbons and refrigerant fluids having an Ozone Depletion Potential (ODP) equal to zero and critical temperatures adequate for fluid evaporation near ambient temperature. Table 2 provides information on chemical formula, critical temperature, Global Warming Potential (GWP) and National Fire Protection Agency (NFPA) safety codes for the considered fluids. All of these fluids are examined in order to obtain general considerations from a thermodynamic perspective. However, in future years, a progressive phase-out may interest high GWP working fluids pushing the fluid choice towards hydrocarbons or novel fluids with a low environmental impact.

Table 2. Characteristics of the investigated organic fluids (GWP stands for global warming potential, NFPA for National Fire Protection Association, H: Health, F: Flammability, I: Instability/reactivity).

Fluid	Formula	Tcrit	GWP	NFPA codes		
				H	F	I
Ethane	CH_3-CH_3	32.2	<10	1	4	
R41	CH_3F	44.1	150	1	4	0
R125	CF_3-CHF_2	66	3500	1	0	0
R143a	CF_3-CH_3	72.7	4470	1	4	0
R32	CH_2F_2	78.1	675	1	4	0
Propylene	CH_2=CH-CH_3	91.1	<10	1	4	0
Propane	CH_3-CH_2-CH_3	96.7	<10	1	4	0
R134a	CF_3-CH_2F	101.1	1430	1	0	1
Iso-butane	$(CH_3)_2$-CH-CH_3	134.7	<10	1	4	0
Iso-butene	CH_2=C-CH_3	145	<10	1	4	0
Butane	CH_3-$(CH_2)_2$-CH_3	152	<10	1	4	0

3. Results and discussion

3.1. Single condensation level cycle

Initially, the analysis is performed without limiting the condensation temperature to values above -45°C. Figure 2 depicts the trend of different variables for the optimized cycles working with diverse organic fluids arranged by critical temperature from the lowest to the highest. The ORC power output (Figure 2.a) is higher for medium-low critical temperature fluids and, in the best cases, the power exceeds 2.2 MW. However, power production from ORC is not sufficient to cover the consumption of the LNG pumps and the BOG compressor plus seawater pumps. The regasification line shows a power deficit and it is at all times necessary to import quantities of electricity to compensate the regasification line unmet and the fixed plant needs. Low critical temperature fluids are characterized by low complexity and a bell-shaped saturation line and they do not therefore allow for dry expansion. The limit on the maximum liquid fraction at the turbine outlet is active (Figure 2.e) binding the optimal condensation temperature (Figure 2.b) that would otherwise be lower in the absence of this constraint. On the other hand, high critical temperature fluids are also more complex and show an overhanging saturation line allowing for dry expansion. However, they also show low condensation pressures (Figure 2.c) that are constrained by the limit on the vacuum at the condenser. This leads to high condensation temperatures, lower temperature differences between evaporation and condensation temperatures, and lower power productions. No fluid is limited by the maximum volume ratio constraint (Figure 2.d). With the exception of ethane, whose optimal condensation temperature is -62°C, most of the other fluids have an optimal condensation temperature close to -45°C.

In a second phase, the analysis is repeated with the additional constraint of a limit in condensation temperature of -45°C required by the use of carbon steel. The variations with respect to the previous case are also reported in Figure 2 represented as black lines. The additional constraint affects the optimization of low critical temperature fluids, whose condensation temperature is now higher than in the previous optimization with a strong reduction of turbine volume ratio and a small increase in vapor quality. ORC power production is slightly penalized. No changes in the final design are obtained for high critical temperature fluids whose condensation temperatures were higher than -45°C also in the previous case. In both cases the most promising fluid is R32 that allows realizing an efficient cycle using only carbon steel for all the components.

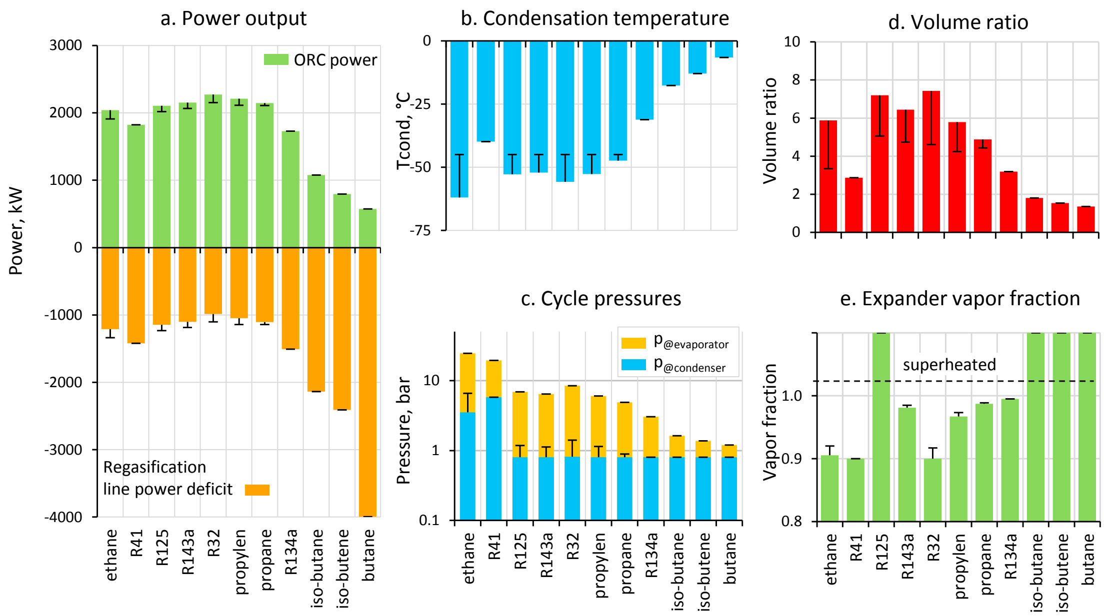

Figure 2. Comparison between single condensation level cycles with various working fluids without a limitation of condensing temperature and with the limit of -45°C (shown as variation with respect to the previous case by way of black lines).

3.2. Double condensation level cycle

The same approach is followed for the optimization of the double condensation level cycle. Figure 3.a depicts the trend of the power output varying the working fluid compared against the results obtained in the previous case reported as black lines. The temperature of the high pressure condenser is constrained to -45°C, whereas lower temperatures are allowed at the low pressure condenser. The increase of power output is remarkable for low to medium critical temperature fluids: R41 is the only fluid that can cover the regasification line power consumption with significant benefits in terms of specific consumption index. For low critical temperature fluids, condensation temperatures of the low pressure condenser fall below -75°C and material selection for heat exchangers and rotating equipment shall take into account the above mentioned condensation temperatures (Figure 3.b). The minimum cycle pressure is constrained by the condenser vacuum limit for all the fluids (Figure 3.c) except R41 that is limited by maximum allowable liquid fraction at expander outlet (Figure 3.e). Volume ratio is divided between the high pressure and the low pressure turbine (Figure 3.d), and the latter one always shows higher variation of volume flow rate according to the lower discharge pressures.

3.3. Optimal plant comparison

The main results referred to the single condensation level cycle with R32 and the double condensation level cycle with R41 are reported in Table 3. The use of the double condensation level cycle allows increasing the ORC power output that is now sufficient to cover the line electrical consumption with a small power surplus of around 21 kW. The specific fuel consumption for the single line becomes negative while the same figure for the overall plant remains positive but it is considerably lower than the ORV technology. In addition a larger percentage (+10%) of the heat required by the LNG gasification is provided by the ORC. On the other hand, the better performances of the double condensation cycle implies more expensive equipment (the low temperature condenser requires suitable materials to withstand the very low temperatures) and installation of two turbines (having an overall volume ratio larger than the one of the single condensation level cycle with R32).

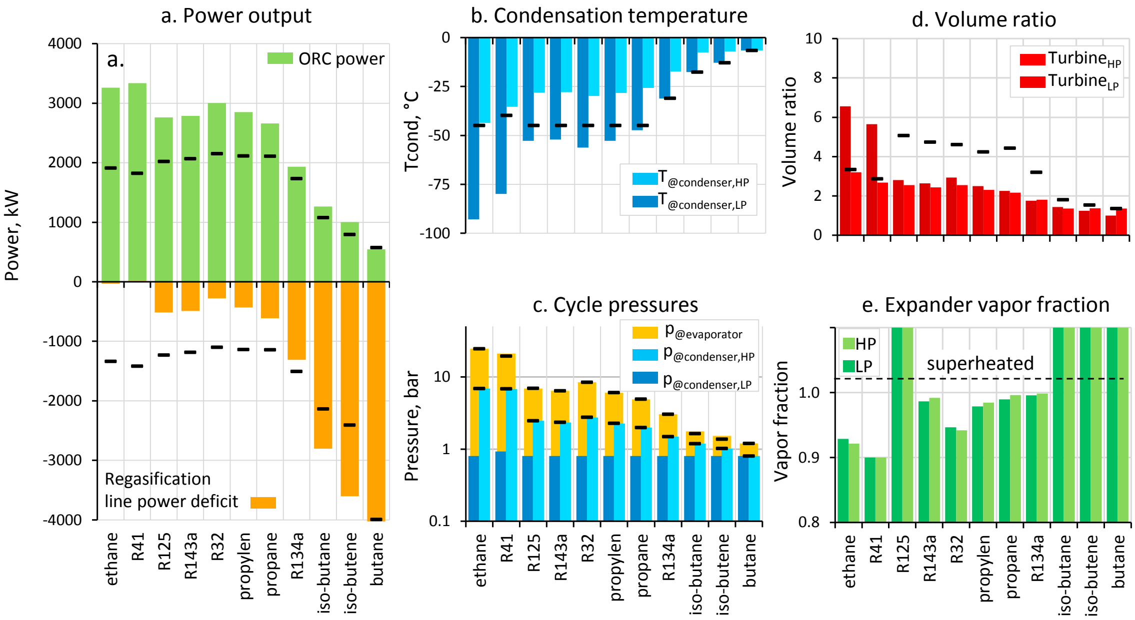

Figure 3. Comparison between double condensation level cycles and single condensation level cycles with various working fluids.

Table 3. Comparison between the optimal single level cycle with R32 and the double condensation level cycle with R41.

Parameter	**Unit**	**R32 Single level**	**R41 double level**	
ORC power output	kW	2152.7	3318.8	
Single line electric deficit	kW	-1101.6	20.6	
% of regasification heat provided by ORC		63.74%	73.83%	
			HP	LP
Volume ratio in expansion		4.6	2.67	5.65
Condensation temperature	°C	-45	-35.3	-79.8
Condensation pressure	bar	1.41	6.8	0.9
Turbine discharge steam quality		0.917	0.9	0.9
Specific Fuel Consumption (single line)	kg/t	1.16	-0.022	
Specific Fuel Consumption (plant)	kg/t	3.52	2.34	

4. Dependency study on seawater temperature

A dependency study on seawater temperature highlights the benefits of warm climate conditions. Table 4 shows the results for seawater temperatures, ranging from 3 to 30°C, solely cases of the optimal single level cycle with R32 and the double condensation level cycle with R41. Increasing the seawater temperature is always profitable since it allows one to increase the evaporation temperature, to improve the power production, and to reduce the specific consumption of both the line and the plant. In the cycle with R41, the increase of evaporation temperature is limited because of the limit of liquid fraction in expansion. Contrarily, the R32 single condensation level cycle is not affected by this constraint and at all times benefits from the seawater temperature increase.

Table 4. Dependency study on seawater temperature for the two selected cycles and comparison of specific consumptions with respect to SCV and ORV technology.

Seawater temperature	6	9	12	21	30
Output power, kW					
Single level R32	2027	2123	2275	2596	2749
Double level R41	3250	3318	3372	3413	3413
Plant Specific Fuel Consumption					
SCV			18.23		
ORV	5.84	5.77	5.77	5.77	5.77
Single level R32	3.65	3.52	3.40	3.08	2.93
Double level R41	2.41	2.34	2.29	2.25	2.25

5. Conclusions

The calculations and results obtained prove that ORC can be a suitable technology to improve the efficiency of LNG regasification terminals which can produce electricity whilst vaporizing the LNG, thus reducing both pollutant emission and the operative costs of the plant. In particular, specific consumption is dramatically reduced compared to both SCV and ORV systems. In spite of the small experience of ORC in this context worldwide, no critical issues are highlighted for the main components. In fact, each component is already used in similar operating conditions in other industrial sectors and the technology transfer should not present any major difficulties.

Among the cycle configurations investigated and the various working fluids that can be used within the cycle, two promising cycles are selected, both of which use a light hydrofluorocarbon (R41 and R32) while cycle layout can be very simple (single condensation level) or more complex (dual condensation level). Power production is favorably affected by higher turbomachinery efficiency, higher seawater temperatures and more complex cycle layouts. However, the main drawback of the adoption of ORC technology is the large increment of heat exchanger surface mainly because of the small temperature differences in the ORC evaporator. Future steps in the work will include a techno-economical optimization of the system taking plant investment costs into account.

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