Liquefaction of natural gas in offshore installations: effects of irreversibilities and composition of natural gas

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Abstract:

The use of natural gas in the energy matrix has been gaining prominence on the world scenery, due to being a fuel with available reserves and being less pollutant than other fossil fuels. Gas pipelines can be hard to build when oil and gas production takes place in deep waters and at a great distance from the coast. An alternative is to liquefy natural gas at the production site (LNG). The LNG can then be transferred to land by methane tankers. Offshore natural gas liquefaction is strongly limited by weight and available space on vessels. In this work, three natural gas liquefaction processes are evaluated (Joule-Thomson cycle, reverse Brayton cycle and Claude cycle). The main objective is to evaluate the sensitivity of each type of technology to the main irreversibilities present: isentropic efficiencies, pressure drop and minimum temperature differences in heat exchangers. Each system is modeled in the ASPEN-Hysys environment, with Peng-Robinson equations of state. After validating the modeled systems, sensitivity studies are performed on the main sources of irreversibility for each system. The effect of the composition of the natural gas to be liquefied on the performance of the systems was also analyzed. The obtained results showed that design parameters (and the irreversibilities associated with them) produce enormous effects on the performance of the liquefaction systems, indicating that compromises between weight and space available in the FPSO may imply the adoption of non-optimized systems in terms of exergy efficiency.

Keywords:

Offshore oil and gas production; Natural gas liquefaction systems; LNG; Exergy efficiency.

1. Introduction

Natural gas (NG) is increasing it's participation in the world energy matrix. Among the fossil fuel, NG is the less pollutant and have the smaller CO_2 footprint. Although the COVID-19 pandemic decreased the economic activities in the world, the war among Russia and Ucrania introduced large concerns on NG availability and energy security. The international trade of NG was greatly affected, specially in Europe.

As any gaseous fuel, NG presents difficulties concerning its transport and distribution. The most used form of transport today is the use of gas pipelines as a link between producers, intermediaries and consumers. However, this solution has as its main disadvantage the fact that when the distances involved are large, the risks involving gas pipelines, such as leaks, increase significantly [1]. This problem is amplified when the production is made offshore, due to the difficulties associated with the launching pipelines at deep water and at long distances from the coastline. This is the case for NG produced in the Brazilian Pre-Salt oil and gas fields. Today, most of the gas produced (associated gas) is re-injected in the oil field. Although this is positive to maintain the pressure in the oil field, the gas is not delivered to the market and is not monetized.

There are a considerable international experience in the transport and trade of NG in liquefied form (LNG) using specialized ships. Various LNG production and export facilities are distributed in producing countries and various re-gasification facilities exists in importing countries. This is the only viable form to deliver natural gas for long distances. LNG production facilities are positioned aside the production fields, onshore. However, when the gas field is offshore, some specialized floating production units (FLNG) were proposed and constructed. An analysis presented by [2] points to this option as a “game changer” in the same way that FPSO enabled oil production in deep water. However, this will depend on the performance and economics of the few pioneer FLNG in operation. There are great challenges to be overcome: weight, topside deck available space, meteorologic and oceanographic conditions. Figure 1 shows preliminary CAPEX and capacity figures of some FLNG units. As for 2022, there are six units in operation: Prelude (Australia), Satu and Dua (Malaysia), Hilli Episeyo (Cameroon), Coral Sul (Mozambique) and Tango (Congo Brazzaville - a barge).

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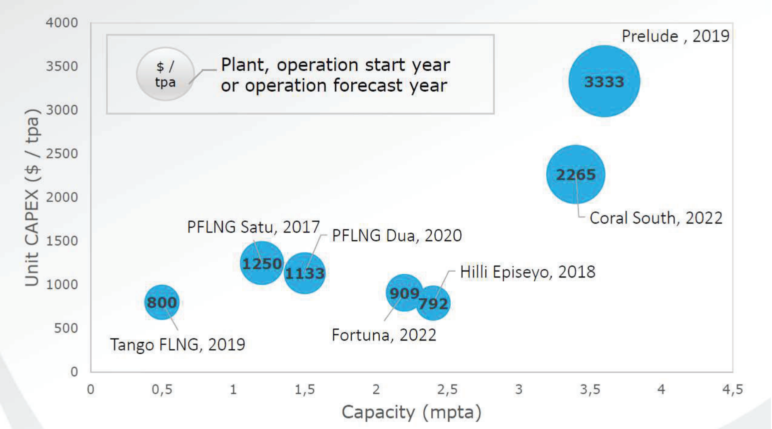

Figure 1. CAPEX and capacity for FLNG in operation or construction. Source: [3]

The heart of a FLNG is the cryogenic system. There are many different cryogenic cycles being proposed to LNG production, both for land or offshore units. The cycles can be classified by the type of refrigerating fluid (pure substances, or mixed substances) and by the type of expansion adopted: Joule-Thomson effect obtained by expansion valves, or adiabatic expansion obtained by turbo-expanders. There is also the possibility to use both effects, like in the Claude cycle.

For land systems, weight, size and complexity are not great concerns, and various researchers presented comparison among different system [4], or optimization of systems [5,6]. A comprehensive review for cryogenic cycles can be found in [7]. Due to the restrictions posed by floating production, specific FLNG systems have been explored. A simplified mixed refrigerant cycle (N_2, CH_4, C_2H_6 and C_3H_8) with dual pressure is proposed in [8] and a good specific power consumption of 1150 kJ / kg of LNG was obtained. A cryogenic cycle based on a reverse Brayton cycle is presented and analyzed in [9]. This cycle uses N_2 as working fluid.

Usually the NG to be liquefied is also pressurized, to reduce the size of the equipment. Using this characteristic, [10] proposes that the last stage for LNG production uses of an expansion valve in the NG line to obtain the final product, LNG at near atmospheric pressure.

Looking for small systems, [11] compares three cycles: one with mixed refrigerant and dual expansion, and two reverse Brayton cycles also with dual expansion, one of them with N_2 and another with CH_4 as working fluids. Based on the hypothesis adopted, the mixed refrigerant presents a better performance: ~1500 kJ / kg of LNG versus 2500 and 2100 kJ / kg of LNG for mixed refrigerant, dual expansion with N2 and dual expansion with CH4. Another work [12] uses data from a Brazilian FPSO gas production and composition, and obtains similar results.

It is difficult to compare the performance of the various systems due to different hypothesis adopted by each author. Some papers does not present all hypothesis adopted, specially those associated with the main irreversibilities: compressors and expanders isentropic efficiencies, pressure losses in the heat exchangers and pipes, approach temperatures in heat exchangers. This work intends to evaluate the effect of irreversibilities and the effect of NG composition on the performance of three cryogenic cycles.

2. Methodology

The cryogenic systems analyzed in this work are described in the next section. All equipment are supposed to operate in the steady-state. Mass and energy conservation was the first step in the simulation of each control volume identified in the flowsheets. Using the entropy balance, entropy generation was calculated to avoid thermodynamic pitfalls in heat exchangers. The exergy balance was used to calculate the irreversibilities and exergy components to obtain performance parameters.

Aspen-Hysys software was adopted to calculate thermodynamic properties of the different flows, using the Peng-Robinson equation of state. All simulated cycles were validated using the same cycles, hypothesis and values of parameters present in [7].

Equation (1) shows the exergy balance for a control volume in the steady-state

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$$0 = \dot{Ex}_Q - \dot{Ex}_W + \textstyle\sum_{in}(\dot{Ex}) - \sum_{out}(\dot{Ex}) - E\dot{x}D, \tag{1}$$

where $\dot{Ex}_Q$ is the exergy associated with a heat flow, $\dot{Ex}_W$ is the available power, $(\dot{Ex})$ are the exergy flow associated with the masses crossing the control surface and $E\dot{x}D$ is the destroyed exergy inside the control volume, also known as irreversibility. The exergy flow $(\dot{Ex})$ is determined by the Eq.(2):

$$\dot{Ex} = \dot{m}[h - h_0 - T_0(s - s_0) + ex^{ch}], \tag{2}$$

where ex^{ch} is the chemical exergy per mass unit. The environment is supposed at 25°C and 1 atm and the chemical exergy, when needed, was obtained according to [13] methodology.

Three performance parameters were calculated: the exergy efficiency, shown in the Eq. (3), the liquid power needed to produce 1 kg of LNG in the Eq.(4), and the energy needed to produce LNG as a percentual of the Lower Heating Value (LHV) of LNG, Eq. (5):

$$\eta_{Ex} = \frac{\dot{Ex}_{LNG} - \dot{Ex}_{NGin}}{|\dot{W}_{net}|} \tag{3}$$

$$\frac{W}{m} = \frac{\dot{W}_{net}}{\dot{m}} = \frac{\dot{W}_{compressors} - \dot{W}_{expanders}}{\dot{m}_{LNG}} \left[\frac{kJ}{kg\ LGN}\right] \tag{4}$$

$$\%\mathrm{LHV} = \frac{\dot{W}_{net}}{\dot{m}_{LNG} * LHV} \ . \tag{5}$$

3. Simulated cycles and its validation

Three cycles were selected in this study: one based in the Joule-Thomson effect, one reverse Brayton cycle and one Claude cycle. All cycles chosen were compatible with [7], which was the reference for model validation.

3.1. Joule-Thomson cycle

The J-T cycle flowsheet in presented in the Fig. 2. The working fluid is compressed in three stages K- , with water cooling E- , and the expansion valve VLV-100 produces the final cooling effect. The working fluid in the cycle is a mixture of components, with the composition given in the Table 1. The composition of the mixture can be changed if desired, to obtain a better match with the NG cooling temperature path. The NG to be liquefied enters the cold box LNG-100 in the state 10 at 5 MPa and 298 K and exits in state 11 at 5 MPa and 113 K.

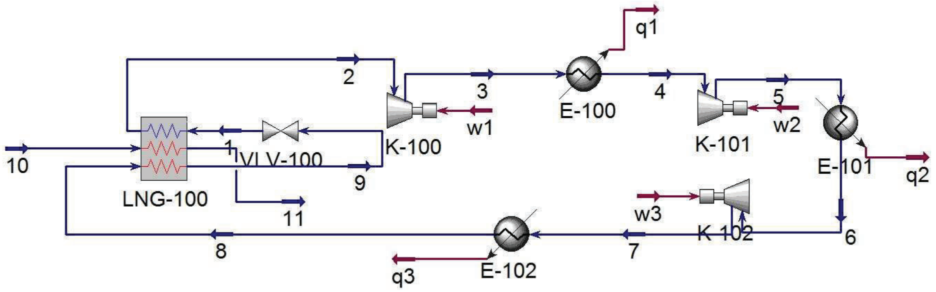

Figure 2. Joule-Thomson cycle.

Table 1. Mixed refrigerant composition for the J-T cycle

Substance	Molar fraction (%)
N_2	8.6
CH_4	30.1
C_2H_6	24.3
C_3H_8	37.0

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3.2. The reverse Brayton cycle

The flowsheet of this cycle is presented in the Fig.3. In the reverse Brayton cycle, the working fluid is N_2. The refrigerant in compressed in three stages, with water cooling. The expansion is done by a turbo-expander (K-103). The NG to be liquefied enters the first heat exchanger LNG-100 and is pre-cooled. The final liquefaction occurs in the heat exchanger LNG-101. Again, the NG is at a constant pressure of 5 MPa, enter the system at 298 K and exits at 113K.

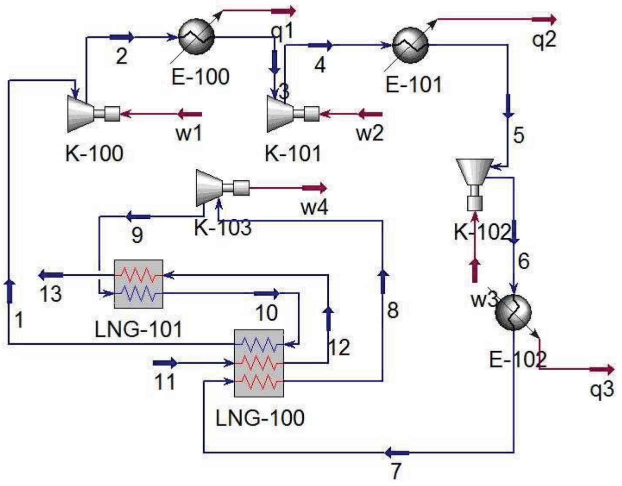

Figure 3. Reverse Brayton cycle

3.3. The Claude cycle

The Claude cycle is shown in the Fig.4. The NG to be liquefied is cooled through the heat exchangers LNG-100 to LNG103. The inlet and outlet conditions of the NG is the same as the two previously presented cycles: 5 MPa, constant, 298 K at inlet and 113 K at outlet. The cooling cycle is somewhat more complex, with four stages of compression, with water cooling, and the expansion process is made by expansion valves and turbo-expanders. The working fluid is pre-cooled in the heat exchanger LNG-100 and then is splitted in two streams. One of them goes to the turbo-expander K-104, mixes with the return stream in the MIX-100 and then passes in the heat exchanger LNG-101. The second stream passes LNG-101, LNG-102 where is cooled, goes to the expansion valve VLV-100 and finally enters the heat exchanger LNG-103. The return stream goes to LNG-102, LNG-101 and LNG-100 to close the cycle.

This cycle uses a NG as the working fluid, with composition given in the Table 2, which is the same adopted for the NG to be liquefied.

Table 2. Natural gas composition adopted for model validation.

Substance	N_2	CH_4	C_2H_6	C_3H_8	$n-C_4H_{10}$	$i-C_4H_{10}$
Molar composition (%)	1.0	91.0	5.0	2.0	0.6	0.4

3.4. Validation of the simulation

It is important to mention that [7] presents results for a great number of **ideal** cycles, always considering the production of 1 kg/s of LNG. Pressure losses, minimum approach temperatures and isentropic efficiencies for compressors and expanders are not considered. The cycles simulated in this work were validated against the values presented in [7] for the simplest cycle of each type (J-T, Brayton, Claude) using the same data, and good results were obtained. The relative deviations on exergy efficiency, Eq. (3), were -1.2% for the J-T cycle, +0.2% for the reverse Brayton cycle and 0,0% for the Claude cycle. Main results of the validation of this work are presented in the Table 3, showing also the exergy efficiency of [7].

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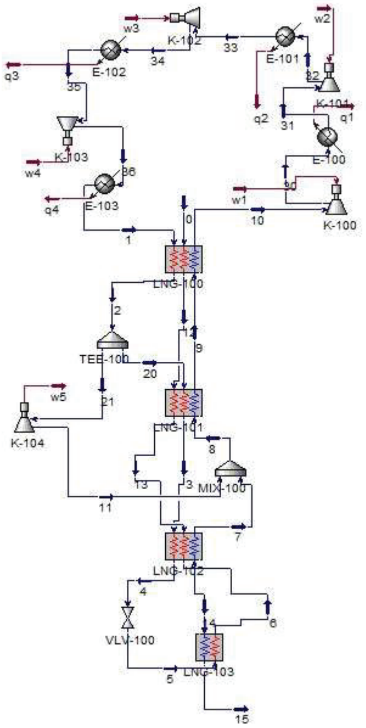

Figure 4. The Claude cycle

The obtained results are overestimated, since important sources of irreversibility were not considered. The use of exergy efficiency is not usual outside academic circles. The most usual parameter to define a good performance for LNG production is presented in the third column in the Table 4: energy expressed in kWh needed to produce 1 kg of LNG. The best practical systems developed for onshore complex installations are in the range of 0.2545 - 0.3572 [4] and for offshore values in the range of 0.400 to 0.474 according to one equipment provider [14].

Table 3. Main results from the validation process

Parameter Cycle	W/m [kJ / kg LNG]	W/m [kWh / kg LNG]	Energy/ LHV %	η_{Ex} %	η_{Ex} % [7]
J-T	795.9	0.2211	1.64	56.4	57.1
Reverse Brayton	743.4	0.2065	1.53	60.4	60.3
Claude	752.8	0,2091	1.56	59.7	59.7

4. Results and discussion

This section shows the effects of irreversibilities as well as the effects of the NG composition on the performance of the basic cryogenic cycles presented.

4.1. Influence of the irreversibilities on cycle performance

This work evaluates three types of irreversibilities: isentropic efficiencies of compressors and expanders, pressure losses in heat exchangers, and minimum approach temperatures in heat exchangers. To evaluate the isolated effect of each irreversibility source, a parametric study was made. The isentropic efficiency was varied in the range from 80-100%; pressure losses were evaluated in the range 0-5% as a percentage of inlet pressure of each stream; minimum approach temperatures in the heat exchangers were evaluated in the range 0-10°C. Ideal cycles have 100% isentropic efficiencies, 0% pressure losses and minimum approach temperatures of 0°C. To analyze each parameter, the other ones were maintained at the ideal values.

It is important to note that the results for exergy efficiency presented in this section for ideal (base) cycles are different from the results presented for the same ideal cycles presented in the Table 3. This is due the fact that the NG composition is different from the one adopted in [7] and presented in Table 2. To this study, a typical composition of the NG produced in the Brazilian Pre-Salt was adopted. So, to obtain the maximum exergy efficiency a new optimization should be made. This is a clear proof of the dependency of the performance of each cycle to the NG composition, effect which will be analyzed in the next section.

Table 4 presents the results of the parametric analysis for the Joule-Thomson cycle. This cycle uses mixed refrigerant with the composition given in Table 1 and reaches a maximum pressure of 5,0 MPa. From the results, it is clear that the minimum approach temperature is the main irreversibility effect, followed by the isentropic efficiency of the compressors. Pressure losses are also relevant, although less important than the other effects. The importance of the minimum approach temperature is due to the mismatch among the NG composition and the composition of the mixed refrigerant, and emphasize the importance of the adjustment of the working fluid composition to each NG composition.

Table 4. Parametric analysis for the Joule-Thomson cycle.

Parameter	Value	Exergy Efficiency	W/m [kJ/kg LNG]	W/m [kWh/kg LNG)	Energy / LHV %
Isentropic efficiency	100%	49.5	720.1	0.2000	1.49
	90%	44.6	800.1	0.2223	1.65
	80%	39.6	900.1	0.2500	1.86
Pressure loss	0%	49.5	720.1	0.2000	1.49
	2%	48.0	738.7	0.2052	1.53
	5%	45.9	766.9	0.2130	1.58
Approach T (°C)	0.0	49.5	720.1	0.2000	1.49
	5.0	30.1	1185.3	0.3293	2.45
	10.0	22.2	1604.0	0.4455	3.31

The results obtained for the reverse Brayton cycle are presented in the Table 5. This cycle operates with N2 as working fluid and its maximum pressure is very high: 10 MPa. The cycle adopts a turbo-expander to obtain the desired minimum temperature. Due to the high pressure needed from compressors and the use of the turbo-expander, the main irreversibility in this cycle is the isentropic efficiency of the rotating machines. Minimum approach temperatures and pressure losses are clearly secondary effects, although important.

Table 5. Parametric analysis for the reverse Brayton cycle.

Parameter	Value	Exergy Efficiency	W/m [kJ/kg LNG]	W/m [kWh/kg LNG)	Energy / LHV %
Isentropic efficiency	100%	52.2	683.4	0.1898	1.41
	90%	31.7	1124.0	0.3122	2.32
	80%	19.2	1859.6	0.5165	3.84
Pressure loss	0%	52.2	683.4	0.1898	1.41
	2%	47.5	742.9	0.2064	1.53
	5%	41.7	833.9	0.2316	1.72
Approach T (°C)	0.0	52.2	683.4	0.1898	1.41
	5.0	48.4	736.8	0.2047	1.52
	10.0	44.9	794.6	0.2207	1.64

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Table 6 presents the results obtained for the Claude cycle. The working fluid for the Claude cycle is NG, but with composition as given by Table 2. There is a mismatch among composition of the NG as working fluid and the NG to be liquefied. This cycle also operates with very high pressure (10 MPa) and uses a turbo-expander as well as a expansion valve to obtain the needed minimum temperature. Since there are rotating machines, mismatch among the working fluid and NG to be liquefied, and a great number of heat exchangers, all irreversibilities are important, including pressure losses.

As seen in Tables 4 to 6, the irreversibilities can have a huge effect on the performance of the cycles.

Table 6. Parametric analysis for the Claude cycle.

Parameter	Value	Exergy Efficiency	W/m [kJ/kg LNG]	W/m [kWh/kg LNG)	Energy / LHV %
Isentropic efficiency	100%	44.3	805.1	0.2236	1.66
	90%	30.9	1154.4	0.3207	2.39
	80%	21.4	1662.2	0.4617	3.43
Pressure loss	0%	44.3	805.1	0.2236	1.66
	2%	41.6	839.6	0.2332	1.73
	5%	37.9	893.8	0.2483	1.85
Approach T (°C)	0.0	44.3	805.1	0.2236	1.66
	5.0	41.9	851.9	0.2366	1.76
	10.0	39.5	903.7	0.2510	1.87

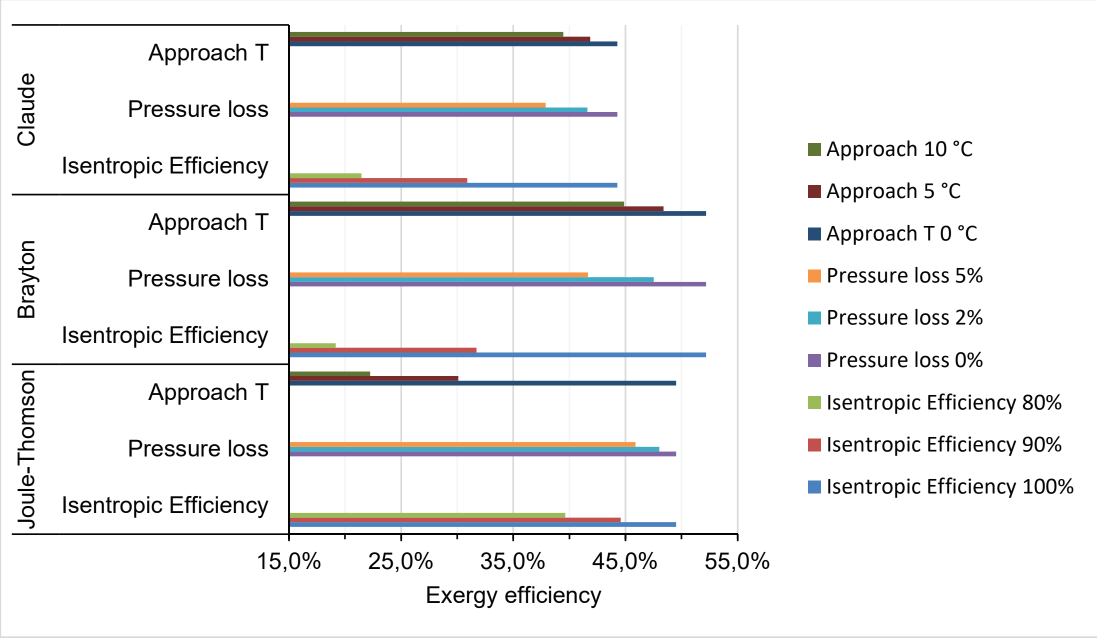

Figure 5. Effects of irreversibilities on the exergy efficiency for the three cycles.

Figure 5 shows the effects of irreversibilities on the exergy for the three cycles. As can be observed, each cycle presents different impacts from each parameter. Since all cycles use compressors, the isentropic efficiency is relevant for all of them. The mismatch of working fluid and NG properties can induce a great impact on performance due to high values of minimum approach temperatures.

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4.2. Influence of the natural gas composition

The operation of a FLNG is foreseen to 20 to 25 years in a given gas oil and gas field. The composition of the NG to be liquefied varies during the field operation, even after the needed treatment before liquefaction. As became clear in the previous section, NG composition impacts the performance of the cryogenic cycles.

To evaluate the effect of NG composition, five NG compositions were adopted. These compositions are presented in the Table 7 and are associated to different years of a typical production curve. The first one corresponds to the third year, when occurs the maximum production of oil and gas. The second composition is for the production year 12. The third composition corresponds to the year 15, when the oil and gas production begins to fall and water content increases. The fourth composition occurs at the 50% BSW (Basic Sediment and Water) condition. Finally, the fifth composition corresponds to year 21, in a condition with maximum water and CO_2 in the oil field. It must be said that all compositions are obtained after the pretreatment phase.

Table 7. NG composition for five field operation conditions.

	NG molar Composition (%)				
Substance	1	2	3	4	5
H_20	0.0000	0.0000	0.0000	0.0000	0.0000
N_2	0.7288	0.7370	0.7516	0.6706	0.7092
CO_2	2.6845	2.8480	2.9941	2.9861	3.2325
C1	75.0549	75.5498	75.9309	75.7151	78.3747
C2	10.8992	10.6941	10.6156	10.0091	9.3585
C3	7.1086	6.7848	6.4926	6.9561	5.5985
i-C4	0.9802	0.9244	0.8666	1.0153	0.7384
n-C4	1.6498	1.5593	1.4594	1.7246	1.2269
i-C5	0.2859	0.2763	0.2620	0.3035	0.2189
n-C5	0.4886	0.4795	0.4590	0.5156	0.3830
C6	0.0616	0.0697	0.0733	0.0592	0.0648
C7	0.0481	0.0632	0.0767	0.0383	0.0760
C8	0.0084	0.0119	0.0155	0.0057	0.0160
C9	0.0012	0.0017	0.0023	0.0007	0.0023
C10+	0.0002	0.0003	0.0004	0.0001	0.0004

Three scenarios for irreversibilities effects were explored. The Base Case is the ideal condition: isentropic efficiencies of 100% for all rotating machines, no pressure loss, and minimum approach temperature of 0°C whenever possible. For the Case 1, irreversibility parameters are in an intermediate value. Isentropic efficiencies are 90%, pressure losses are 2% of the inlet pressure for each heat exchanger, and minimum approach temperature is 5°C. Case 2 represents the worst condition for all parameters: isentropic efficiencies are 80%, pressure losses are 5% of the inlet pressure for each heat exchanger, and minimum approach temperature is 10°C.

As an example of the thermodynamic states for each stream, Table 8 presents the results for condition 1 (NG composition for the third year of field operation) for the three scenarios using Joule-Thomsom cycle. The streams are numbered according to Fig.2.

The thermodynamic states for the reverse Brayton and Claude cycle are not presented here due to space limitation for the paper.

The effect of NG composition and degree of irreversibilities on the performance of the Joule-Thomson cycle is presented in the Table 9. The degree of irreversibility is the dominant effect, causing huge reductions on the exergy efficiency, whatever is the NG composition. As an example, for NG composition 2, the exergy efficiency falls from 52.5% (base case) to 27.6% for case 1 and to 14.4% to case 2. The effect of NG composition, however, for the same level of irreversibility (case), is also relevant. In the example, the exergy efficiency vary in the range from 5 to 17% depending on the NG composition. And it must be remembered that the NG composition didn't vary so much, as can be seen in the Table 7. The J-T cycle uses mixed refrigerant. To improve the performance of the cycle, the molar percentage of the constituents of the working fluid should be optimized for each NG composition, bringing operational complexity for the FLNG.

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Table 8. Thermodynamic conditions of the streams. Joule-Thomson cycle, NG composition 1

	Stream	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Base case	vapor fraction	0.045	1.000	1.000	1.000	1.000	1.000	1.000	0.564	0.000	1.000	0.000
	Temperature (C)	-160.2	24.9	67.4	24.9	70.3	24.9	77.2	24.9	-160.2	24.9	-160.2
	Pressure (kPa)	402.3	402.3	949.5	949.5	2241	2241	5300	5300	5300	5000	5000
Case 1	vapor fraction	0.101	1.000	1.000	1.000	1.000	1.000	1.000	0.564	0.000	1.000	0.000
	Temperature (C)	-165.2	19.9	89.3	24.9	97	24.9	106.2	24.9	-160.2	24.9	-160.2
	Pressure (kPa)	111.8	109.8	406.1	398.1	1473	1443	5410	5300	5194	5102	5000
Case 2	vapor fraction	0.139	1.000	1.000	1.000	1.000	1.000	1.000	0.564	0.000	1.000	0.000
	Temperature (C)	-170.2	14.9	112.7	24.9	125.4	24.9	135.8	24.9	-160.2	24.9	-160.2
	Pressure (kPa)	41.9	39.9	211.6	200.6	1063	1010	5570	5300	5035	5236	5000

Table 9. Performance of the Joule-Thomson cycle. Different NG compositions and degrees of irreversibilities

NG Composition	Degree of irreversibility	Exergy efficiency	W/m [kJ /kg LNG]	W/m [kWh/kg LNG]	Energy / LHV %
1	Ideal	49.52%	720.1	0.200	1.49
	Case 1	26.48%	1339.9	0.372	2.77
	Case 2	16.90%	2082.4	0.579	4.30
2	Ideal	52.48%	684.2	0.190	1.41
	Case 1	27.59%	128.1	0.358	2.66
	Case 2	14.41%	2426.8	0.674	5.01
3	Ideal	50.09%	721.6	0.200	1.49
	Case 1	26.78%	1342.8	0.373	2.77
	Case 2	17.10%	2086.6	0.580	4.31
4	Ideal	49.71%	719.3	0.200	1.49
	Case 1	26.58%	1338.5	0.372	2.77
	Case 2	16.96%	2080.4	0.578	4.30
5	Ideal	51.31%	727.5	0.202	1.50
	Case 1	27.42%	1354.0	0.376	2.80
	Case 2	17.50%	2105.0	0.585	4.35

Table 10 shows the performance for the reverse Brayton cycle. The overall tendencies are similar to J-T cycle - that is, the degree of irreversibility is the main effect. Since the working fluid for this cycle is N_2, the effects of NG composition is near 3.5%, not so great as for J-T cycle. Since this cycle operates with very high pressures and uses various rotating machines, the effects of irreversibilities on exergy efficiencies are even greater than for the J-T cycle: from 54% (base case) to 28% in case 1 and 14% in the case 2.

The performance of the Claude cycle is presented in the Table 11. The effect of irreversibilities on performance is again the predominant: the exergy efficiency drops from 45% in the base case to 31.5% in case 1 and to 20.3% for case 2. The effect of the NG composition for a given level of irreversibility is in the range of 3.7 to 6.0%.

Table 10. Performance of the reverse Brayton cycle for different NG compositions and different degrees of irreversibilities

NG Composition	Degree of irreversibility	Exergy eff	W/m [kJ /kg LNG]	W/m [kWh/kg LNG]	Energy / LHV %
1	Ideal	52.2%	683.4	0.190	1.41
	Case 1	27.4%	1286.6	0.357	2.66
	Case 2	14.3%	2423.7	0.673	5.01
2	Ideal	52.5%	684.2	0.190	1.41
	Case 1	27.6%	1288.1	0.358	2.66
	Case 2	14.4%	2426.8	0.674	5.01
3	Ideal	52.7%	685.5	0.190	1.42
	Case 1	27.7%	1289.7	0.358	2.66
	Case 2	14.5%	2430.0	0.675	5.02
4	Ideal	52.4%	682.7	0.190	1.41
	Case 1	27.5%	1285.3	0.357	2.66
	Case 2	14.4%	2421.4	0.673	5.00
5	Ideal	54.1%	690.6	0.192	1.43
	Case 1	28.4%	1300.6	0.361	2.69
	Case 2	14.8%	2451.7	0.681	5.07

Table 11. Performance of the Claude cycle for different NG compositions and different degrees of irreversibilities

NG Composition	Degree of irreversibility	Exergy eff	W/m [kJ /kg LNG]	W/m [kWh/kg LNG]	Energy / LHV %
1	Ideal	44.3%	804.6	0.224	1.66
	Case 1	31.2%	1118.9	0.311	2.31
	Case 2	20.3%	1669.8	0.464	3.45
2	Ideal	44.3%	809.6	0.225	1.67
	Case 1	31.3%	1124.2	0.312	2.32
	Case 2	21.3%	1596.6	0.444	3.30
3	Ideal	44.6%	810.7	0.225	1.68
	Case 1	31.6%	1120.7	0.311	2.32
	Case 2	20.2%	1694.3	0.471	3.50
4	Ideal	44.7%	799.4	0.222	1.65
	Case 1	31.3%	1117.9	0.311	2.31
	Case 2	20.0%	1695.7	0.471	3.50
5	Ideal	46.4%	803.8	0.223	1.66
	Case 1	32.4%	1126.7	0.313	2.33
	Case 2	20.6%	1714.9	0.476	3.54

Figures 6 and 7 present comparisons among the three cycles, focusing on exergy efficiency and work to produce 1 kg of LNG respectively. As expected, the work needed increases (and the exergy efficiency decreases) when the irreversibilities increases. It is interesting to note, however, that for a given cycle and a given level of irreversibility, the NG composition can produce a higher exergy efficiency associated with a smaller work to produce 1 kg of LNG. Mass, energy and approach temperatures details can explain this.

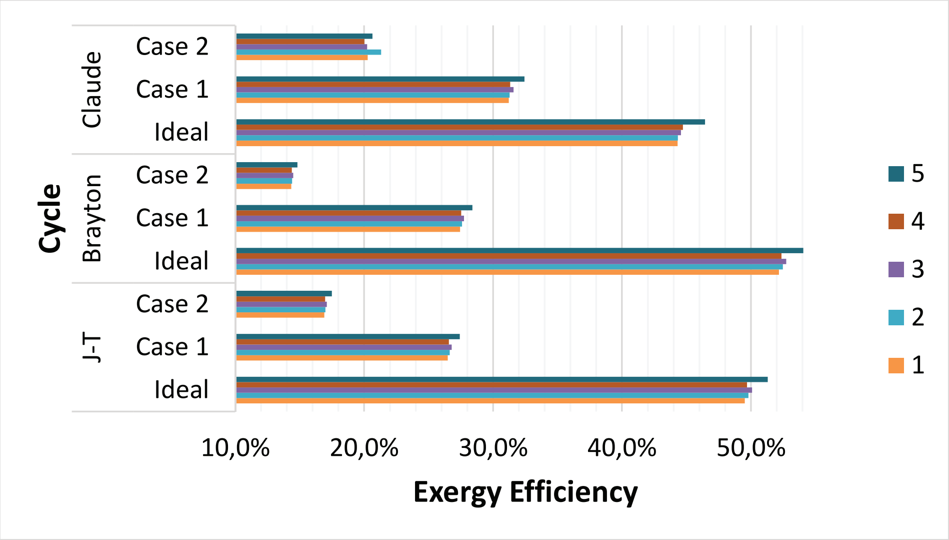

Figure 6. Performance comparisons among the three cycles: exergy efficiency.

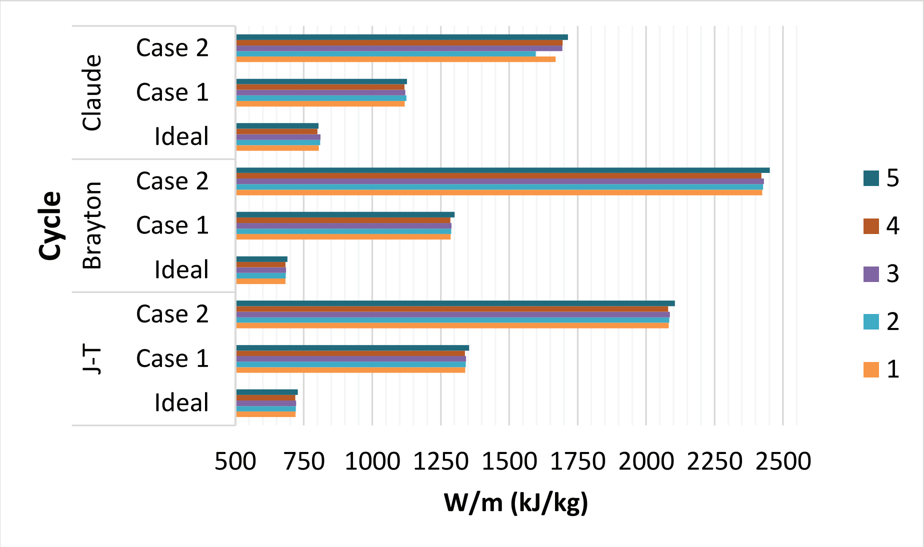

Figure 7. Performance comparisons among the three cycles: work to produce 1 kg of LNG.

5. Concluding remarks

The analysis developed in this work showed the huge influence of the irreversibility level on the performance of three cycles proposed to produce LNG offshore. The limitation of weight and size induces a design which uses as few components as possible. Then, the three cycles studied were the simplest of each class. The influence of the NG composition, although smaller, is also relevant.

The use of mixed refrigerants is interesting to reduce the internal heat transfer irreversibilities in heat exchangers, but requires an optimization of the working fluid composition (molar fractions of the components) associated with the NG composition. This is the case for the analyzed J-T and Claude cycles.

The use of N_2 in a reverse Brayton cycle presented less dependency of the NG composition. However, this cycle proved to be the most sensitive to the isentropic efficiencies of the rotating machines - that is, the design of highly efficient compressors and turbo-expanders must be the focus for a better performance of this cycle.

The prime movers to run the compressors can be electrical motors, or thermal machines as gas turbines. The work needed to produce 1 kg of LNG didn't take into account the use of fuel to run the prime mover or to generate the electricity. As an example, if a gas turbine fueled by NG, with 35% of efficiency, is used as mechanical drive, the use of fuel can be in the range of 5-15% of the available NG, depending on the cycle and level of irreversibilities.

To reduce the volume of the equipment, the NG to be liquefied was assumed at 5 Mpa to increase its density. The power needed to compress the NG to this pressure was not taken into account. Depending on details of the FLNG design and pretreatment processes, the NG can be at some pressure grater than atmospheric.

For the cycles analyzed, in the conditions specified in this work, the exergy efficiency varied from 43 to 52% for the ideal cycles, to 14 to 17% for cycles with high level of irreversibilities. This indicates that the feasibility of FLNG is quite sensible to a balance among high efficiency and cycles as simple as possible to save size, weight and economic costs.

Nomenclature

h -	Enthapy [kJ/kg]	LHV -	Lower heating value [kJ/kg]	$\dot{Ex}$	Exergy flow [kJ/s]
$\dot{m}$ -	Mass flow [kg/s]	$\dot{Ex}_Q$ -	Exergy flow -heat transfer [kJ/s]	η_{Ex}	Exergy efficiency
s -	Entropy [kJ/(kg.K)]	$\dot{Ex}_W$ -	Exergy of power [kJ/s]	NG	Natural gas
T -	Temperature [K]	$E\dot{x}D$ -	Destryed exergy [kJ/s]	LNG	Liquified natural gas
$\dot{W}$ -	Power [kW]	ex^{ch} -	Chemical exergy [kJ/kg]	FPSO	Oil and gas platform

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