Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 4859 – 4865

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Performance Increase of a Small-Scale Liquefied Natural Gas Production Process by Means of Turbo-Expander

M. A. Ancona*, M. Bianchi, L. Branchini, A. De Pascale, F. Melino

DIN - Alma Mater Studiorum University of Bologna – Viale del Risorgimento 2 - 40136 Bologna, Italy

Abstract

In the last years, the growing demand of the energy market has led to the increasing penetration of renewable energy sources in order to achieve the primary energy supply. However, in the next years fossil fuels are expected to remain the dominant energy source, due to the forecasted increase of global energy consumption. In particular, the natural gas is predicted to still play a key role in the energy market, on account of its lower environmental impact than other fossil fuels. Natural gas is currently employed mainly as gaseous fuel for stationary energy generation, but also as liquefied fuel, as an alternative to the diesel fuel, in vehicular applications. Liquefied Natural Gas (LNG) is currently produced in large plants directly located at the extraction sites.

The aim of the study is the definition of an optimal small-scale production process for LNG, to be realized – in opposition to the current habit – directly at filling stations. With this purpose, two different LNG production layouts have been proposed and investigated within a thermodynamic analysis: starting from a Joule-Thompson LNG expansion process, a new layout with a turbo-expander has been proposed for the natural gas liquefaction. The carried-out simulations show that the new proposed solution allow to optimize the LNG production process and to minimize the process' energy consumption.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Liquefied Natural Gas; small-scale production; filling stations; energy evaluations; optimization.

1. Introduction

Although the increased penetration of renewable energies, in the next years fossil fuels are expected to remain the dominant energy source, due to the forecasted increase of global demand for energy [1, 2]. In particular, due to its lower environmental impact than other fossil fuels [2, 3], natural gas is predicted to be the key source. In more detail, the International Energy Agency (IEA) predicted that the demand for Natural Gas (NG) will be more than 50% higher than the 2014 levels by 2040 [2], with an estimated consumption growth of about the 1.9% per annum from 2012 to 2035 [4]. Furthermore, also the Liquefied

* Corresponding author. Tel.: +39-051-2093320; fax: +39-051-2093313.
E-mail address: maria.ancona2@unibo.it.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.963

Natural Gas (LNG) is becoming interesting in transports as an alternative to diesel fuel [5], allowing a decrease in pollutant emissions and a reduction of about the 50% in fuel's costs [6].

At present, LNG is produced at large-scale plants by means of three main production processes: (*i*) a cascade process, with three separate refrigeration cycles, operating with different pure refrigerants at three evaporation temperature levels and multistage compressions [7, 8]; (*ii*) a mixed refrigerant process, consisting in a single cycle with a mixture of different refrigerants [9, 10] and (*iii*) an expander process, seldom applied, by means of expanders instead of Joule-Thompson valves [11, 12]. After the production, LNG is transported by ship, stored and distributed to final users, with an overall cost comparable with the cost of the liquefaction process [13].

On the other hand, small-scale LNG production plants are currently rare and mainly realized in order to reduce the workload on gas reservoirs sites [14] or for offshore compact LNG production [15].

In this scenario, this study aims to define an optimal LNG production process to be sited directly at the refueling stations, allowing to avoid – in particular – the economic and environmental costs of LNG transportation. In particular, a novel turbo-expansion liquefaction process has been proposed in order to improve the LNG production performance.

2. Case studies and assumptions

The first of the two LNG production processes considered for the analysis (Case 1) is shown in Figure 1. As it can be seen from Figure 1, the layout is composed of a primary line and of a secondary line. The natural gas hailing from the distribution grid (section 1), mixed with a recirculation stream from the secondary line (16), is cooled in the heat exchanger HE 3 before entering into the first compression train C1 (3), where the pressure is increased until its maximum cycle value (7).

Then, after the cooling of the NG stream provided by the heat exchangers HE 2 (section 8) and HE 1 (section 9), the LNG is produced by means of a Joule-Thomson valve (TV, section 10). Finally, the liquid fraction (11) is separated in a flash tank and sent to the storage tank, while the vapor fraction (12) is recirculated, providing for the cooling effect in the heat exchangers HE 1 and HE 3 and being compressed with the compression train C2 (16) before the mixing with the NG supply stream. The cooling effect of the heat exchanger HE 2, instead, is provided by means of a compression chiller working with ammonia refrigeration fluid.

The development of this layout has been the object of Authors' previous work [16], along with a in-depth sensitivity analysis about the effect of maximum cycle pressure (*i.e.* p_7), storage pressure (*i.e.* p_{10}) and chiller cooling effect (*i.e.* T_8) on the process performances. The results of this investigation have been set as starting point for the here-presented study (see Table 1). All the simulations have been carried-out with the assumption of producing 1 kg/s ($\dot{m}_{LNG}$ in Table 1) of LNG to be sent to the LNG storage tank. Furthermore, the compression train C1 is supposed to be inter-cooled and after-cooled with air cooled heat exchangers, while – as a result of the parametric optimization analysis carried out in [16] – there is no need of inter-cooling for the compression train C2.

In this study, a new layout for LNG production is introduced and considered (Case 2), as presented in Figure 2: here a turbo-expander is considered instead of the Joule-Thompson throttle valve, in order to improve the performance of the process and to reduce the electric energy consumption. The remaining part of the layout is not modified in respect to the Case 1, as well as the main process input parameters listed in Table 1. In addition, an isentropic efficiency equal to the 70% [17] has been considered for the turbo-expansion process.

Relating to the inter-cooled compression train, the total required pressure ratio has to be opportunely split between the two compression stages. In this study, the minimum compression specific work criterion

– including the pressure losses due to the inter-cooling and the after-cooling – has been applied, as developed in [16].

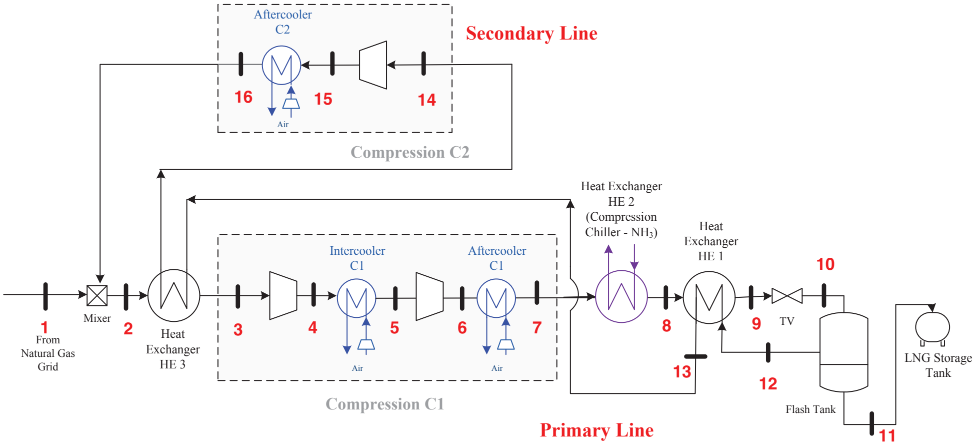

Fig. 1. LNG production layout with Joule-Thompson isenthalpic valve (Case 1) [16]

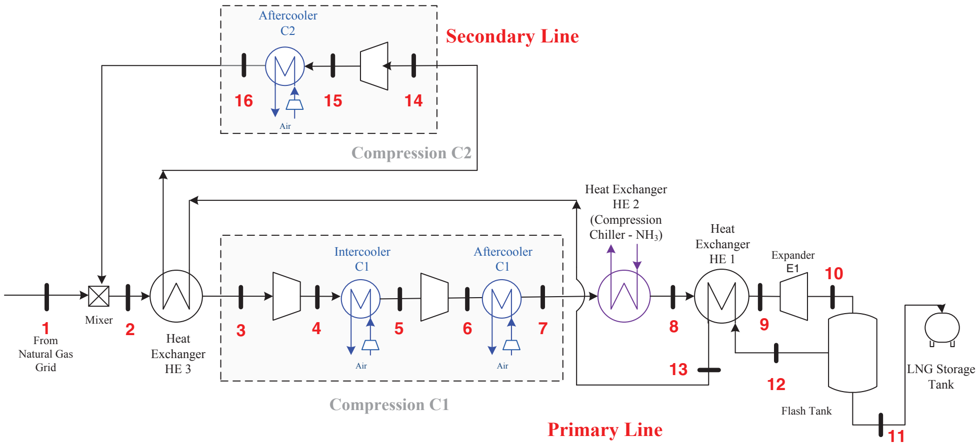

Fig. 2. LNG production layout with turbo-expander (Case 2)

Table 1. Main input for the analyzed cases

NG composition	[-]	100 % CH_4			
T_1	[°C]	20	ε (heat exchanger HE 1)	[-]	0.70
p_1	[bar]	30	p_{10}	[bar]	15
T_3	[°C]	-5	$\dot{m}_{LNG}$	[kg/s]	1
p_7	[bar]	200	EER compression chiller	[-]	1.1
p_{16}	[bar]	30	T_8	[°C]	-50
$\eta_{P,Ci}$, i = 1, 2	[-]	0.76[(*)]	$T_5 = T_7 = T_{16}$	[°C]	30
$\eta_{em,Ci}$, i = 1, 2	[-]	0.90	Pressure losses (each HE)	[-]	2%

[(*)] Value of polytropic efficiency corresponding to a set of existing commercial machines.

The two presented LNG production processes have been simulated with an in-house developed software [16] enabling to obtain the physical conditions of the fluid for each section of the layouts and to determinate the heat exchange and the electric consumption of the various plant components.

3. Results and discussion

The energy results obtained for the two analyzed liquefying processes – along with the percentage variation achievable in Case 2 compared to Case 1 – are comparatively listed in Table 2, while the corresponding thermodynamic diagram *Log P-h* is shown in Figure 3. As it can be seen, the introduction of the turbo-expander instead of the throttle valve allows to considerably decrease the electric energy consumption, obtaining an electric energy saving of about the 20%. This evidence can be easily explained if considering the thermodynamics of the two different liquefying processes. Due to the non-isenthalpic expansion process (see Figure 3), indeed, the quality of the fluid in section 10 results lower for Case 2 than for Case 1. Thus, the input mass flow rate of natural gas, necessary to produce 1 kg/s of LNG, is lower and, as a consequence, also the electric energy consumption of the compression trains and of the chiller decreases, being fixed the other parameters. In more detail, the quality achievable at the end of the expansion process decreases from the value of 0.510 of Case 1 to a value equal to 0.403 for Case 2, corresponding to a mass flow rate through the primary line equal to 1.674 kg/s (instead of 2.041 kg/s as for the Case 1).

Table 2. Electric energy results of the analyzed cases and achievable saving percentage with the turbo-expansion process

		Case 1 (throttle valve)	**Case 2 (expander)**	**Percentage variation [%]**
Compressor 1 electric consumption (P_{C1})	[kW]	1079	885	-18
Compressor 2 electric consumption (P_{C2})	[kW]	209	142	-32
Chiller electric consumption ($P_{chiller}$)	[kW]	583	479	-18
Total electric consumption	**[kW]**	**1871**	**1506**	**-20**
Expander electric production (P_{E1})	[kW]	-	81	
Total net electric consumption	**[kW]**	**1871**	**1425**	**-24**

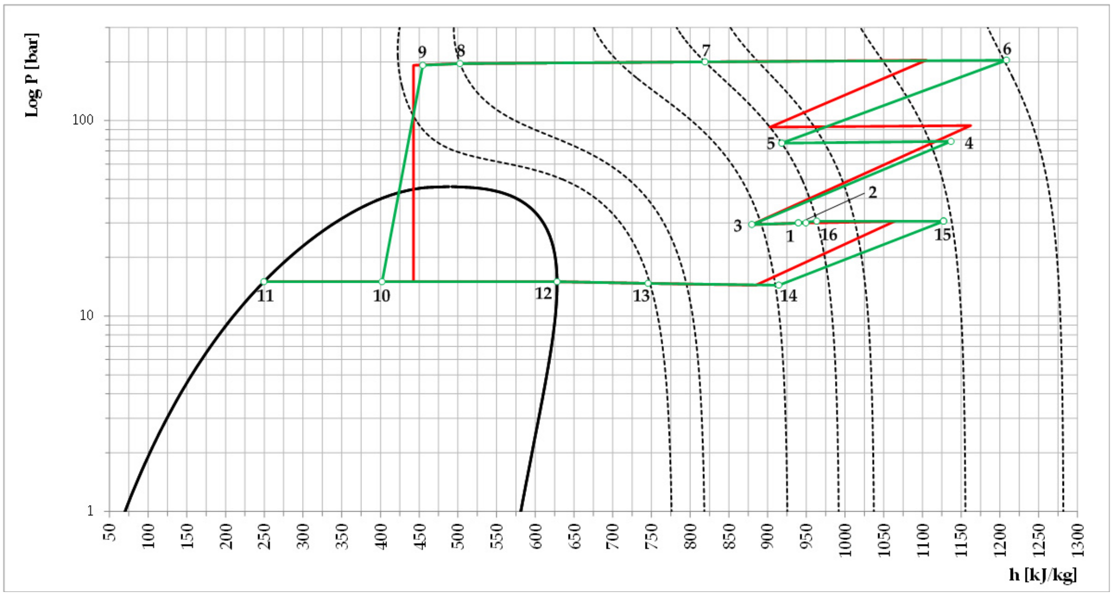

Fig. 3. Thermodynamic diagram of the process obtained for the Case 2 (in green) and comparison with the Case 1 (red line)

Furthermore, the power produced by the expander in Case 2 – even if the amount of electric energy produced is not substantial – could be recovered and used for internal process consumptions, allowing to reach the 24% of external electric energy consumption decrease.

Relating to the thermal energy exchange occurring during the liquefaction process, the results of the analysis are listed in Table 3, along with the percentage variation achievable with Case 2 compared to Case 1. The decrease in the heat exchanged by HE 1 and HE 3, achievable with Case 2, is due to the decrease in mass flow rate and – contemporarily – entails a modification in the temperature level at the inlet of the compression train C2 (*i.e.* T_{14} increase). This is an essential further advantage, since for Case 1 the temperature T_{14} results very low (around -10 °C), representing the lower limit for the integrity of compressors (as reported by the main compressors' manufacturers).

As well as for the Case 1, for the turbo-expansion liquefying process there is no need of inter-cooling during the compression C2, but the increase of the temperature T_{14} implies a slight increase in the heat exchanged by the after-cooler AC-C2. On the other hand, relating to the compressor train C1, the decrease of the cooling loads is due to both the decreases of the mass flow rate and of the temperature at the end of the first compression stage.

Table 3. Thermal energy results of the analyzed cases and achievable saving percentage with the turbo-expansion process

		Case 1 (throttle valve)	**Case 2 (expander)**	**Percentage variation [%]**
Q_{HE1}	[kW]	122	79	-35
Q_{HE3}	[kW]	144	114	-21
Q_{IC-C1}	[kW]	524	481	-8
Q_{AC-C1}	[kW]	575	508	-12
Q_{AC-C2}	[kW]	105	109	+4
IC+AC thermal exchange	**[kW]**	**1204**	**1098**	**-9**
Total thermal exchange	**[kW]**	**1470**	**1291**	**-12**

4. Concluding remarks

The aim of this study is the analysis of a small-scale solution for the NG liquefaction, in order to produce pressurized LNG to be used in the transport sector. A LNG optimized production process has been defined, in order to give a *plug & play* solution for vehicles' fueling, placed directly at the refueling stations. In this study, starting from a Joule-Thompson production cycle (Case 1) – optimized through a parametric analysis in a previous Authors' work – a new layout (Case 2, turbo-expander liquefaction process) for LNG production has been proposed in order to improve the performance of the cycle. The turbo-expander technology suitable for cryogenic conditions is currently available on the market but rarely employed for LNG production.

The results of the analysis show that the replacement of the Joule-Thompson valve by means of a turbo-expander allows to considerably reduce the energy consumption of the LNG production process. More in detail, the electric energy consumption can be reduced of about the 20%, due to the decrease of the NG mass flow rate required to produce the same amount of LNG, as direct consequence of the reduction of the quality at the end of the expansion process (*i.e.* non-isenthalpic turbo-expander instead of Joule-Thompson isenthalpic process). Furthermore, if considering the possibility to recover the electric energy produced by the turbo-expander, the electric energy saving increases up to the 24%, a very significant value considering that Case 1 is already an optimized solution. Finally, also the heat to be removed during the process by means of external fluids (*i.e.* inter-cooling and after-cooling sections with air cooled heat exchangers) is reduced of around the 9% by employing the turbo-expansion liquefying process. Consequent advantages in terms of required space and investment costs for the heat exchangers can be obtained, allowing – along with the consumption decrease – to counterbalance the higher investment cost of the turbo-expander with regard to the throttle valve. In-depth economic evaluations will be further investigated in future works.

Nomenclature

C	Compressor
E1	Expander
EER	Energy Efficiency Ratio
HE	Heat Exchanger
IEA	International Energy Agency
LNG	Liquefied Natural Gas
$\dot{m}_{LNG}$	mass flow rate
NG	Natural Gas
p	pressure
P	electric power
Q	thermal power
T	temperature
TV	Throttle Valve
ε	effectiveness
η_{em}	electro-mechanical efficiency
η_P	polytropic efficiency

References

[1] The outlook for energy: A view to 2040. http://www.exxonmobil.com/Corporate/Files/news_pub_eo2012.pdf.
[2] World Energy Outlook 2014; International Energy Agency (IEA).
[3] Natural Gas Issues and Trends; U.S. Energy Information Administration (EIA), April 1998.
[4] BP Energy Outlook 2035. http://www.bp.com/energy outlook.
[5] http://www.lng24.com.
[6] Gowid S, Dixon R, Ghani S. Profitability, reliability and condition based monitoring of LNG floating platforms: A review. *Journal of Natural Gas Science and Engineering* 2015;**27**:1495–1511.
[7] Martin P-Y, Fischer B. In: Natural Gas Liquefaction Processes Comparison, 14th International Conference and Exhibition on Liquefied Natural Gas (LNG-14), Doha, Qatar, March 21−24, 2004.
[8] Bosma P, Nagelvoort RK. In: Liquefaction Technology; Developments through History, 1st Annual Gas Processing Symposium, Doha, Qatar, January 10−12, 2009.
[9] van de Graaf JM, Pek B. Large-capacity LNG Trains – The Shell parallel Mixed Refrigerant Process. In: Business Briefing: LNG Review, 2005.
[10] Berger E, Forg W, Heiersted RS, Paurola P. The MFC®(Mixed Fluid Cascade) Process for the First European Baseload LNG Production Plant. Linde, 2003.
[11] Waldmann IB. Evaluation of Process Systems for Floating LNG Production Units. In: Tekna Conference, June 18−19, 2008.
[12] Foglietta JH. Production of LNG using Dual Independent Expander Refrigeration Cycles. In: AIChE Spring National Meeting, New Orleans, LA, March 10−14, 2002.
[13] Lim W, Choi K, Moon I. Current Status and Perspectives of Liquefied Natural Gas (LNG) Plant Design. *Industrial & Engineering Chemistry Research* 2013;**52** (9):3065–3088.
[14] He T, Ju Y. Optimal synthesis of expansion liquefaction cycle for distributed-scale LNG (liquefied natural gas) plant. *Energy* 2015;**88**:268–280.
[15] Remeljej CW, Hoadley AFA. An exergy analysis of small-scale liquefied natural gas (LNG) liquefaction processes. *Energy* 2006;**31**:2005–2019.
[16] Ancona MA, Bianchi M, Branchini L, De Pascale A, Melino F, Mormile M, Palella M.. A Novel Small Scale Liquefied Natural Gas Production Process at Filling Stations: Thermodynamic Analysis and Parametric Investigation. *Proceedings of the ASME Turbo Expo*. Volume 9, 2016. DOI: 10.1115/GT2016-56463
[17] Li Y, Wang X, Ding Y. An optimal design methodology for large-scale gas liquefaction. *Applied Energy* 2012;**99**:484–490.