Applied Thermal Engineering 137 (2018) 142–153

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

On-site LNG production at filling stations

M.A. Ancona[a,*], M. Bianchi[a], L. Branchini[a], A. De Pascale[a], F. Melino[a], M. Mormile[b], M. Palella[b]

[a] DIN – Alma Mater Studiorum, Viale del Risorgimento 2, 40136 Bologna, Italy
[b] Graf S.p.a., Via Galileo Galilei 36, 41015 Nonantola, MO, Italy

HIGHLIGHTS

- Development and modelling of alternative solutions for small-scale LNG production directly at filling stations.
- Thermodynamic analysis and performance evaluation on different proposed solutions.
- Definition of performance indicators for the comparison between the proposed cases.
- Parametric analysis in order to minimize the process energy consumption.

ARTICLE INFO

Keywords:
Liquefied natural gas
Small-scale production
Filling station
Energy performance evaluation
Parametric analysis

ABSTRACT

In the next decades fossil fuels are expected to still play a fundamental role within the energy market, contemporarily to the increased exploitation of renewable energy sources. Among all fossil fuels, natural gas is predicted to be the key source to achieve the satisfaction of the forecasted increase in energy demand, due to its lower environmental impact. In particular, great attention is being paid on the transport sector where liquefied natural gas can be seen as an interesting opportunity. In this context, this paper aims to elaborate a novel solution for liquefied natural gas production directly at filling stations. With this purpose, in this work four different liquefaction process layouts will be proposed and analyzed, considering natural gas supply grid operating at middle pressure or at low pressure. The developed configurations will be analyzed by applying an in-house developed calculation model, which enables to define the physical conditions in each section of the process and the energy fluxes of the plant.

In order to define a configuration which allows to minimize the process' energy consumption, a parametric analysis has been carried out to evaluate and compare the performance of the proposed processes. With this purpose, several performance indicators have been defined and applied to the considered scenarios.

1. Introduction

In the last years, a sustainable energy production turn into a fundamental issue due to the forecasted increase in energy demand, with a predicted average rate of 0.9–1.6% per year [1,2]. Since its environmental impact is lower than other fossil fuels [2,3], Natural Gas (NG) is expected to play a key role in the energy market for the years to come. In 2014, indeed, the International Energy Agency (IEA) estimated that – from 2014 to 2040 – the global demand of energy will grow by 37% and, contemporarily, the demand of NG will increase more than the 50% [2].

In transport sector, NG can be used either as Liquefied Natural Gas (LNG) or Compressed Natural Gas (CNG). However, LNG is preferable due to the lower required volume: compared to natural gas, indeed, the volume of LNG is 600 times inferior at ambient temperature, while the CNG volume is only 1% less of its original value [4]. On the other hand, if compared to diesel fuel, the LNG price results for about the 50% cheaper [5]. For these reasons, the employment of LNG will certainly increase in the next years and, in 2035, it is expected to account for the 15% of the total NG consumption [6].

At present, LNG is mainly produced in large-scale plants located close to the NG extraction sites. Here, the NG is treated after the extraction, in order to be purified from undesirable substances (*i.e.* acid gas, water, mercury, heavy hydrocarbon, etc.), and usually liquefied through of one of the following processes:

1. a cascade process, by means of Joule-Thompson valves and based on different pure refrigerants (usually three), working at different temperature levels [7–12];
2. a mixed refrigerant process, developed to decrease the amount of

* Corresponding author.
E-mail address: maria.ancona2@unibo.it (M.A. Ancona).

https://doi.org/10.1016/j.applthermaleng.2018.03.079
Received 19 October 2016; Received in revised form 22 December 2017; Accepted 22 March 2018
Available online 23 March 2018
1359-4311/

Nomenclature

A	pressure losses coefficient [–]
c_P	specific heat at constant pressure [kJ/kg K]
e	total specific electric energy consumption [kJ/kg]
HR^*	heat rate [–]
k	heat capacity ratio [–]
LHV	lower heating value [kJ/kg]
LHV_R	fuel residual lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
P	electric power [kW]
p	pressure [bar]
Q	thermal power [kW]
S	heat exchanger surface [m^2]
T	temperature [°C]
U	global thermal exchange coefficient [kW/m^2 °C]
x	quality [–]

Greek symbols

β	pressure ratio [–]
ε	heat exchanger effectiveness [–]
η	efficiency [–]
ρ	fuel degradation index [–]

Subscripts and superscripts

1,…,18	process sections of main interest
el	electric
em	electro-mechanical
POL	polytropic
R	residual
ref	reference
tot	total

Acronyms

C1	Compression train #1
C2	Compression train #2
CNG	Compressed Natural Gas
EER	Energy Efficiency Ratio
HE	Heat Exchanger
LNG	Liquefied Natural Gas
NG	Natural Gas
TV	Throttle Valve

required equipment regarding to the cascade process. This liquefaction process is composed by a single cycle employing mixture of refrigerants (mainly nitrogen and hydrocarbons, such as methane, ethane and propane) [13–26];

3. an expander process, based on the use of expanders instead of Joule-Thompson valves [27–34].

On the other hand, small-scale LNG production facilities are currently rare and mainly realized in order to reduce the workload on gas reservoirs sites [35] or for offshore compact LNG production [36]; in particular, based on [37], the number is 12 in 2015. Furthermore, this kind of plant is not common at refueling stations. Relating to the liquefaction process for small-scale applications, at present the main applied technologies consist of N_2 expander cycle and single-mixed refrigerant process (SMR) [38,39]. The SMR process efficiency strongly depends on the optimization of mixed refrigerant composition and on the ambient conditions [38] and the power consumption of this process is usually lower than the N_2 expander cycle one. On the other hand, the efficiency of the latter is almost independent of feed gas condition. Moreover, nitrogen is a nonreactive refrigerant, then the safety is greater [40]. Yuan et al. have studied a small-scale NG liquefaction process adopting single nitrogen expansion with the aim to minimize the unit energy consumption. They demonstrate that the system is compact, reliable and it shows a good adaptability to the feed gas condition [41]. In [42] a novel NG liquefaction process is presented: this process allows to liquefy, without energy consumption, part of NG employing the pressure exergy of the pipeline. However, the system efficiency depends on the pipeline pressure and if it is too low the process may not work [42]. Finally, Jokinen et al. presented a mathematical model for the optimization of a small-scale LNG supply chain [43], which is mainly focused on the device and parameters concerning the NG side. In particular, this solution is designed to be directly installed at the vehicle's filling stations, in this way the costs relative to the transport of LNG are avoided.

In this scenario, the idea of generating LNG directly at filling stations has been developed, in order to give a compact solution and to avoid the economic and environmental costs related to LNG transportation by ship, contemporarily promoting LNG as fuel in transport sector. Furthermore, with respect to the processes usually applied in small-scale applications, this study is aimed to the realization of simpler – and, as a consequence, less expensive – solutions that can be competitive in the future global energy scenario.

In particular, the proposed approach is thought as an alternative to the current habit of LNG filling stations, as it can be seen from Fig. 1 (red dotted line), where the whole NG value chain – from the natural gas extraction to the final users – is summarized and presented. As it can be observed from the figure, the production of LNG at filling stations enables to eliminate the ship transportation, the secondary storage and the road transport of LNG: thus, even if a small-scale process presumably penalizes the conversion efficiency (with respect to large scale facilities), the environmental and energy related costs can be considerably reduced.

Obviously, the proposed idea can be seen not only as an alternative to the LNG production at the extraction sites, but also in addition to this habit: since the existing LNG plants are expected to be not enough to meet the increasing global need, in the next years the number of LNG production plants is predicted to significantly raise.

In Fig. 2, the current global liquefaction plants are presented as

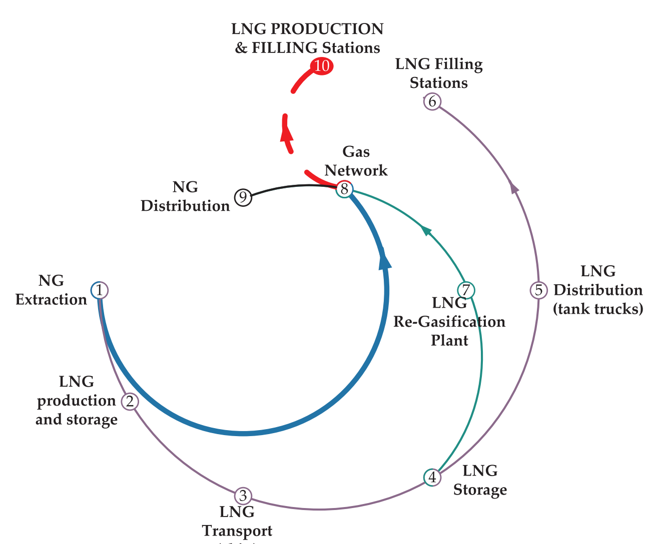

Fig. 1. NG value chain from extraction to final users.