Fuel xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Fuel

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

Exergy analysis of combined simultaneous Liquid Natural Gas vaporization and Adsorbed Natural Gas cooling

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H I G H L I G H T S

- LNG–ANG coupling is an effective method of LNG physical exergy utilization, especially in the case of LNG satellite gasification stations.
- efficiency of LNG exergy utilization by LNG–ANG coupling can achieve up to 24%.
- comparison with the most often used Ambient Air Vaporizer shows high superiority of LNG–ANG coupling.

A R T I C L E I N F O

Article history:
Received 18 January 2013
Received in revised form 15 March 2013
Accepted 27 March 2013
Available online xxxx

Keywords:
Liquefied Natural Gas
Adsorbed Natural Gas
Exergy analysis
LNG regasification
LNG physical exergy

A B S T R A C T

The liquefaction process of Natural Gas (NG) involves high energy consumption. Although this energy expenditure is partly offset by benefits in LNG transportation there is a need of improving the balance of the LNG process chain. Nowadays the cost of liquefaction of LNG oscillates between 0.45 and 0.55 kW h/kg when the thermodynamic minimum is 0.30 kW h/kg (assuming the composition is 100% methane). The proximity of these numbers means that the possibility of improving the liquefaction process is very limited. A different approach to the problem allows LNG as a source of exergy which can be utilized by combining LNG gasification with other processes to be considered. Such solutions can help optimize the economical balance of the overall LNG process chain. The paper proposes a novel idea of coupling the LNG regasification with the filling process of Adsorbed Natural Gas (ANG) tanks. Latent heat of LNG vaporization is directly used for the precooling of the ANG adsorption bed. This enables gas compressors to be avoided and improves the competitiveness of the ANG storage method which is an alternative to Compressed Natural Gas (CNG) storage and distribution. Exergy analysis presented in the article allows the proposed idea and conventional methods of Natural Gas regasification to be compared.

1. Introduction

Natural Gas is considered to be the most perspective energy source in forthcoming decades. It is recognized as one of the cleanest fossil fuels. The NG share in the global energy market shows a stable growing tendency. The International Energy Agency predicts a 25% share of NG in world primary energy sources in 2035 [1]. This prediction is even higher for countries with rich shale gas resources.

Natural Gas is usually transported from the wellhead to the processing plant and transferred to consumers through high pressure gas pipelines. Transport of NG from remote locations which are separated by large water reservoirs is conducted in its liquid form. Liquefied Natural Gas (LNG) has a high energy density (lower physical volume) around 600 times higher than when in gaseous form. Transportation of NG in its liquid form is also attractive for short time working boreholes, as is also the case with unconventional gas. The LNG share in overall NG turnover shows a stable growing tendency and is expected to exceed 25% soon [2]. Due to this observed increase there is a strong interest in improving the economical balance of the whole LNG process chain.

The LNG process chain is apart of the NG process chain (see Fig. 1) and consists of three steps: liquefaction, transportation and storage and regasification. Perfection in liquefaction technology seems to have achieved its limit approaching the thermodynamic minimum (latest patents indicate the energy of liquefaction as 0.35 kW h/kg of LNG [3] and even less [4]). Storage and transportation systems are very efficient and the only step of the LNG process chain with the potential of thermodynamic, and in consequence economic optimization, is regasification.

2. Exergy of LNG

Exergetic analysis can be considered as a convenient tool for the evaluation of different methods of LNG vaporization.

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.03.074

Nomenclature

B	exergy (kJ)
b	specific exergy (kJ/kg)
$\dot{b}$	exergy stream (kJ/(kg s))
C_p	specific heat capacity (kJ/(kg K))
g	acceleration of gravity (kg m/s^2)
h	specific enthalpy (kJ/kg)
m	mass (kg)
$\dot{m}$	mass stream (kg)
p	pressure (Pa)
s	specific entropy (kJ/(kg K))
T	temperature (K)
v	velocity (m/s)
V	volume (m^3)
z	level (m)

Greek symbol

η	exergy efficiency

Subscripts

0	ambient conditions
AC	active carbon–adsorption bed
ads	adsorption process
ads gas	adsorbed gas
ads NG	Adsorbed Natural Gas
air	air
chem	chemical
el	electrical
f	final
gas	gaseous form
in	inlet
k	kinetic
mech	mechanical
NG	Natural Gas
liq	liquid form
LNG	Liquefied Natural Gas
loss	losses
out	outlet
p	potential
ph	physical
th	thermal
u	utilized
vap	LNG vaporization process

Exergy is the maximum amount of work that can be done by a subsystem as it approaches thermodynamic equilibrium with its surroundings by a sequence of reversible processes [5]. Equilibrium state means uniform temperature and pressure conditions as well as density, chemical composition, gravitational and electro-magnetic fields between the reference state (surrounding) and the final state of the subsystem.

The classical definition of the exergy includes a few types of exergy. Every single type is an effect of the gradient of a specific parameter between the environment and the system state. In Eq. (1) different exergy types are shown: kinetic, potential, mechanical, thermal, chemical and electrical exergy respectively [6].

$$b = b_k + b_p + b_{mech} + b_{th} + b_{chem} + b_{el} \tag{1}$$

Some authors also distinguish nuclear exergy [7], the exergy change of a system caused by magnetism [8], or surface tension. However, it is ignored here as it is not relevant (an assumption concerning the absence of nuclear effects, magnetism and surface tension was made).

For the purpose of the examination of the LNG gasification process, the range of considered exergy types can be limited. Until no combustion occurs there is no need to consider the chemical exergy of Natural Gas. Due to the fact that there is no electrical exergy of the LNG, the corresponding part of Eq. (1) is deleted. The rest of the exergy parts: kinetic, potential, mechanical and thermal are grouped together under the term physical exergy (also named thermomechanical exergy). In conclusion the gasification process can be examined from the point of pure physical exergy conversion.

Eq. (2) presents the formula of the physical exergy where every single part is developed to full mathematical form.

$$b_{ph} = \frac{v^2 - v_0^2}{2} + mg(z - z_0) + [h(T,p) - h_0(T_0,p_0) - T_0[s(T,p) - s_0(T_0,p_0)]] \tag{2}$$

The first part corresponds to the kinetic exergy of the system moving at speed v with respect to the reference surrounding. The second part is responsible for the gravitational potential exergy of the whole system and is determined by means of the height between the system and ground level of the surrounding. The last part describes the thermal and mechanical exergy of the system that depends on the p, T gradient of the system and the environment.

As the input of mechanical exergy (kinetic and potential) is small in comparison to pressure and temperature based exergy

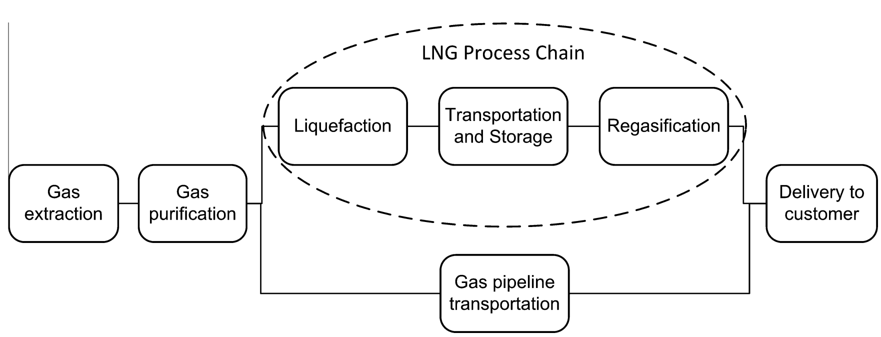

Fig. 1. Natural Gas process chain.

Please cite this article in press as: Roszak EA, Chorowski M. Exergy analysis of combined simultaneous Liquid Natural Gas vaporization and Adsorbed Natural Gas cooling. Fuel (2013), http://dx.doi.org/10.1016/j.fuel.2013.03.074