Applied Energy 115 (2014) 17–24

Contents lists available at ScienceDirect

Applied Energy

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

A novel process for small-scale pipeline natural gas liquefaction

T.B. He, Y.L. Ju *

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China

HIGHLIGHTS

- A novel process was proposed to liquefy natural gas by utilizing the pressure exergy.
- The process is zero energy consumption.
- The maximum liquefaction rate of the process is 12.61%.
- The maximum exergy utilization rate is 0.1961.
- The economic analysis showed that the payback period of the process is quit short.

ARTICLE INFO

Article history:
Received 16 June 2013
Received in revised form 16 October 2013
Accepted 4 November 2013

Keywords:
Liquefaction process
Exergy utilization
Pipeline natural gas
Economic analysis
Process optimization

ABSTRACT

A novel process for small-scale pipeline natural gas liquefaction is designed and presented. The novel process can utilize the pressure exergy of the pipeline to liquefy a part of natural gas without any energy consumption. The thermodynamic analysis including mass, energy balance and exergy analysis are adopted in this paper. The liquefaction rate and exergy utilization rate are chosen as the objective functions. Several key parameters are optimized to approach the maximum liquefaction rate and exergy utilization rate. The optimization results showed that the maximum liquefaction rate is 12.61% and the maximum exergy utilization rate is 0.1961. What is more, the economic performances of the process are also discussed and compared by using the maximum liquefaction rate and exergy utilization rate as indexes. In conclusion, the novel process is suitable for pressure exergy utilization due to its simplicity, zero energy consumption and short payback period.

1. Introduction

With the development of economy, the demand of energy supply is also increasing by 10% per year [1]. Natural gas is a clean fossil fuel which is widely used and can reduce the greenhouse emissions [2]. Natural gas is transported by the gas pipeline with a high pressure (up to 10 MPa) on land. However, the high-pressure natural gas needs to reduce its pressure to 0.4–1.6 MPa in pressure reduction stations with throttling valves. During the throttling process, the available exergy of the high-pressure natural gas is wasted. As a result, the methods to recover the available exergy of the high pressure natural gas will be very important for saving the energy and reducing the greenhouse emissions.

Several researchers have focused on the available exergy utilization of the high-pressure natural gas. Pozivil [3] modeled expansion turbines used in the natural gas pressure reduction stations. Kostowski and Usón [4] presented an expansion system applied in the natural gas transportation process. The system reduced the pressure of the natural gas and provided power to drive the electric generators. A new approach using a hybrid turboexpander-fuel cell system was conducted to recover the available exergy in the natural gas pressure reduction stations [5]. Farzaneh-Gord [6] proposed a system which consisted of preheating and a turboexpander to recover the energy in the natural gas pressure drop stations to generate electricity.

The available exergy in the high-pressure natural gas can also be used to liquefy the pipeline natural gas. A small-scale liquefied natural gas plant was presented by Shen et al. [7] to use the available exergy in the natural gas pressure drop stations. Kirillov [8] introduced the throttling–vortex cycle to produce LNG without energy cost by utilizing the pressure exergy of the compressed gas from pipeline. However, the disadvantage of the cycle is low liquefaction rate (2–4%). The expander liquefaction cycle [9–12] would be available to utilize the pressure exergy of the pipeline natural gas.

Although there are many publications on the design and optimization of LNG liquefaction processes, only a few exists regarding the liquefaction process for utilizing the pipeline pressure exergy. In this paper, a novel process is presented to liquefy the pipeline

* Corresponding author. Address: Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, 800 Dongchuan Road, Minhang District, Shanghai 200240, China. Tel./fax: +86 21 34206532.

E-mail address: yju@sjtu.edu.cn (Y.L. Ju).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.11.016

Nomenclature

a	the attractive parameter (Pa(m^3/mol)^2)
b	the effective molecular volume (m^3/mol)
e_x	unit mass exergy (kJ/kg)
E	exergy (kJ)
h	unit mass enthalpy (kJ/kg)
k_{ij}	binary interaction coefficient
m	mass flow rate (kg/s)
P	pressure (kPa)
Q	heat (kW)
R	universal gas constant
s	entropy (kJ/kg K)
t	temperature (°C)
T	temperature (K)
v	molar volume (m^3/mol)
W	work (kW)
W_{min}	the minimum work of booster (kW)
W_{max}	the maximum work of expander (kW)
y	liquefaction rate (%)
z	mole fraction for the component
η_b	the adiabatic efficiency of booster
η_e	exergy utilization rate
η_{ex}	the adiabatic efficiency of expander

Abbreviations

LLH	liquefied light hydrocarbon
LNG	liquefied natural gas
LMTD	logarithmic mean temperature difference

natural gas by utilizing its available exergy. The process is very simple and without any energy consumption. The thermodynamic analysis of this process is also performed. The liquefaction rate and exergy utilization rate are selected as the objective functions. Several key parameters are optimized to reach the maximum liquefaction rate and exergy utilization rate. Moreover, the economic analysis is adopted in this study to show the initial costs and payback period.

2. Liquefaction process design

As shown in Fig. 1, the natural gas is pressurized by two boosters (Booster-1 and Booster-2) and is cooled by the water-coolers (WC-1 and WC-2) firstly. As it passes through the heat exchanger (HEX-1), its temperature decreases to approximately −48 °C. Then the cold natural gas undergoes the first expander (Expander-1) to reduce its pressure and temperature. Some components are condensed at the same time. In the first separator (S-1), the remaining gas and condensate are separated. The condensate reduces its pressure to 450 kPa by a throttling valve then enters another separator (S-4). Liquefied light hydrocarbon (LLH) can be got from the bottom of S-4. The remaining gas from S-1 undergoes the second expander (Expander-2) and its pressure reduces to approximately 1600 kPa. Afterward, the natural gas enters the separator (S-2). The vapor from S-2 goes back into the heat exchanger to provide the cold energy. Then the vapor from S-2 is imported into the sub-high pressure network (node 19). The liquid reduces its pressure to 450 kPa and goes into the separator (S-3). LNG can be got from the bottom of S-3. The vapor from S-3 mixes with the vapor from S-4 to provide the cold energy for the heat exchanger (HEX-1). Then the mixture gases (node 18) are imported into the medium pressure network. The thermodynamic cycle diagram with each point (T–P) is illustrated in Fig. 2.

In this study, two boosters (Booster-1 and Booster-2) are driven by two expanders (Expander-1 and Expander-2). Except for the energy consumption in the water coolers, the whole process does not need any energy input. The mole fraction of each component for the pipeline natural gas and the known parameters in the process are given in Table 1.

3. Thermodynamic analysis

To determine the performance of the proposed process, the steady-state models in Aspen HYSYS (version 7.3) [13] are used. In this study, every unit operation is modeled with mass and energy balance. Several assumptions are made for the process as followings:

- The process is steady state and steady flow with negligible potential and kinetic energy effects.
- Heat transfer and pressure drop in the pipeline are ignored.
- The pressure drop in the heat exchanger and the water coolers is zero.
- The adiabatic efficiency of two boosters is 75%.
- The adiabatic efficiency of two expanders is 80%.

3.1. Boosters

The pipeline natural gas is firstly pressurized to a higher pressure by the boosters which are driven by the expanders. The required works are given by:

$$\text{Booster}-1: W_1 = \dot{m}_1(h_2 - h_1) = W_{\min 1}/\eta_{b1} \quad (1)$$

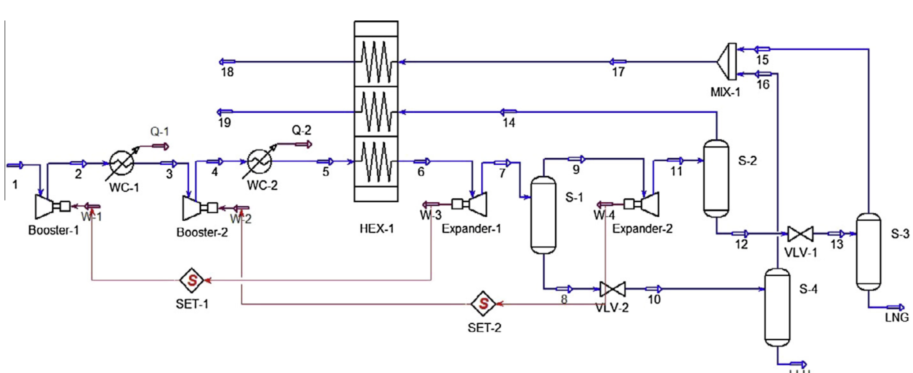

Fig. 1. The flow diagram of the novel liquefaction process.