Energy 158 (2018) 986–1000

Contents lists available at ScienceDirect

Energy

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

Energy and exergy analysis of reciprocating natural gas expansion engine based on valve configurations

Mohsen Jannatabadi [a, *], Mahmood Farzaneh-Gord [b], Hamid Reza Rahbari [c], Abolfazl Nersi [d]

[a] Minoodasht Branch, Islamic Azad University, Minoodasht, Iran
[b] Faculty of Engineering, Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran
[c] The Faculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran
[d] Technical Inspection Supervisor, Golestan Gas, NIGC, Iran

ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form
21 May 2018
Accepted 16 June 2018
Available online 18 June 2018

Keywords:
Natural gas pressure reduction
Genetic algorithm
Expansion engine
Power generation
Exergy efficiency

ABSTRACT

Natural gas pressure should be reduced in city gate stations before consuming. Part of the physical exergy of this high pressure gas is wasted if throttling valves are employed for pressure reduction. Reciprocating natural gas expansion engine (RNGEE) could be utilized to recover most of the physical exergy. In this study, a single acting RNGEE is investigated thermodynamically in order to optimize the ports opening/closing times. For this purpose, cylinder and slide valves and two types of piston valves have been modeled and compared. Based on an exergy analysis, a genetic algorithm has been developed to optimize the valves timing. Moreover, effects of the pressure ratio on the exergetic efficiency and power generation of the RNGEE have been studied numerically. Methane was modeled as a real gas by employing AGA8 equation of state. Results showed that beside importance of exergy efficiency optimization, inlet process period has also critical impacts on engine performance. Moreover, power generation is almost the same while using cylinder or flange valves (~1986 kW/kg) with exergy efficiencies of 83.6% and 82.7% respectively. In contrast, slide and piston valves are found to have lower power generation (1746 kW/kg and 1753 kW/kg respectively) with the exergy efficiency of ~72%.

1. Introduction

Natural gas (NG) extracted from refinery has a high pressure of about 70 bars. In order to transport this high pressure gas to a distribution system where it is being consumed, its pressure should be reduced to a safe and usable level. This is usually done in natural gas pressure reduction stations which sometimes called city gate stations (CGSs). Nowadays In most of countries, throttling valves are used to reduce the gas pressure [1] where the physical exergy of high pressure gas is wasted.

To reduce the amount of exergy destruction, a few configuration has been proposed to be employed in CGSs. A Combined Heat and Power (CHP) system could be employed in CGS for necessary preheating as well as generation the power. A CHP system has been optimized with genetic algorithm (GA) by Sanaye [2]. It was found that the payback period of the investment is 1.23 years. Some CHP technologies such as turbines, rotary and screw expanders have been studied with Badr et al. [3] they have analyzed parameters such as power output, rotational speed. Objective function of actual annual benefit in terms of dollar in natural gas pressure reduction stations has been maximized by Sanaye and Nasab [4] with GA. Results showed that ambient conditions and pressure & mass flow rate of the inlet natural gas has a significant role in selecting the appropriate method for pressure reduction systems. Farzaneh-Gord et al. [5] have analyzed solar heater installation in CGSs through energy and exergy point of view.

There are number of studies on recovering physical exergy of high pressure natural gas during pressure reduction mostly focusing on the pressure exergy recovering devices. The turbo expander and RNGEE are two candidate devices. Bisio has proposed using the mechanical systems to convert pressure exergy of NG into compressed air [6]. Neseli carried out a study focusing on installing turbo expander instead of throttling valve in Izmir [7]. It was shown by Kostowski and Usón [8] that expansion systems such as turbo expander could provide mechanical energy to drive electric

* Corresponding author.
E-mail addresses: m.jannatabadi@minoodashtau.ac.ir (M. Jannatabadi), mahmood.farzaneh@yahoo.co.uk (M. Farzaneh-Gord), rahbarihamidreza@yahoo.com (H.R. Rahbari), abolfazl.nersi@gmail.com (A. Nersi).

https://doi.org/10.1016/j.energy.2018.06.103
0360-5442/© 2018 Published by Elsevier Ltd.

generators. Pressurized gas contains physical exergy could be converted to electricity or may even be utilized directly in particular industrial applications. Kolasinski et al. [9] presented an analytical modeling of rolling piston expander in natural gas expansion due to pressure reduction of NG. They have stated advantages of these expanders against to turbines which are more complicated and expensive. Their results showed the effect of varied sizes of the expander components and natural gas thermal properties at the inlet and outlet of the expander and the expander output power.

In addition of turbo expander, RNGEE could be employed to recover this wasted energy. Fig. 1 shows that RNGEE could be installed in parallel with expansion valve. It can be said using of RNGEE is one of the newest method to recovering and producing energy without any fuel consumption.

Although, there could be a lot of use for NG expansion, to the best of our knowledge, there are not enough academic studies, especially in area of RNGEE. In a report by Dehli [10], using of RNGEE for power generation from natural gas pressure reduction has been introduced. He has shown that, the amount of electrical power generation is depended on the level of inlet temperature, the mass flow rate and the pressure ratio. Effects of geometrical parameters on the rates of power generation and RNGEE performance have been studied by Farzaneh-Gord and Jannatabadi [11]. In another study, Farzaneh-Gord and Jannatabadi [12] studied timing optimization of RNGEE treating methane as an ideal gas. They have studied cylinder valve and shown that exergy destruction due to mixing and heat transfer could be neglected. Moreover, they have shown that pressure ratio has a strong effect on timing optimization too. Farzaneh-gord et al. [13] have studied also the expander installation in town border stations. It was found that the initial investment will be returned after 1.5 years.

Exergy analysis could be used to calculate the amount of RNGEE power generation or amount of work lost [14]. An expansion engine is very similar to a reciprocating compressor, however the work cycle is reverse, consequently studies on reciprocating compressor could be used to model RNGEE [12]. Several sources of exergy destruction have been modeled by different researchers. McGovern and Harte [15] and [16] have identified the exergy destruction sources of compressor and have showed that exergy destruction due to heat transfer and mixing could be neglected in reciprocating compressor.

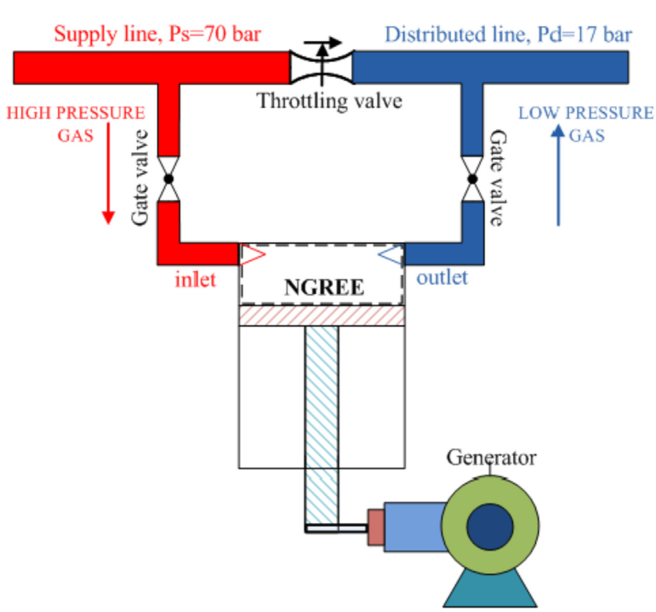

Fig. 1. Installing RNGEE in CGS.

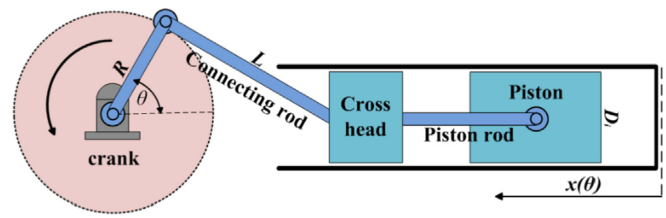

Fig. 2. Slider crank mechanism.

Although, there have been a lot of exergy lost in CGSs but so far a few studies have been carried out to design and optimize RNGEE. In last studies [11] and [12], a single acting expansion engine with just a cylinder valve has been introduced. The effect of geometrical parameters of engine for a sample timing has been simulated in Ref. [11] and in Ref. [12] the effect of these parameters on timing optimization of ports has been shown. In both of these studies the methane has been modeled as an ideal gas. But in this study, the thermodynamic analysis including continuity equation, energy balance and exergy analysis have been used to study a single acting RNGEE and methane is modeled as a real gas. For small scale power generation, turbine should not be used due to complexity and cost [17], but RNGEE could be used for any scale of power reduction. Then for first time, the RNGEE with four different valve configurations in natural gas pressure reduction stations has been studied aiming to recover physical exergy of high pressure natural gas. These four valves are categorized in cylinder, slide, piston and flange types. In this analysis, two valves are moved over two inlet/outlet ports in the cylinder valve, but in other types, a single valve is moved over a port. To calculate exergy flows and exergy lost resources, exergy analysis was used and to obtain optimum timing of ports opening/closing times, exergy efficiency is selected as a fitness function which is maximized using a modified elite genetic algorithm. Also the effect of inlet pressure variation on engine performance has been stated for the first time in this paper.

2. Methodology

RNGEE in-cylinder gas is assumed as control volume for thermodynamic modeling. The model could measure and predict all thermodynamic properties in the expansion chamber as a function of crank angle. The advance numerical simulation model is based on transient governing equations of the continuity and energy (Fig. 2).

2.1. Piston displacement

To convert straight-line motion of mechanical parts to rotary motion, as in a RNGEE, slider crank mechanism should be used [12].

In order to convert all differential equation respect to time to the form of crank angle below equation is used [18]:

$$\frac{d}{dt} = \frac{d}{d\theta}\frac{d\theta}{dt} = \omega\frac{d}{d\theta} \tag{1}$$

Instantaneous piston displacement according to top dead center (TDC) and gas volume can be measured as follows [11]:

$$x(\theta) = x_{cl} + R(1 - \cos\theta) + L\left\{1 - \sqrt{1 - \left(\frac{R}{L}\right)^2 \sin^2\theta}\right\} \tag{2}$$