Energy xxx (2015) 1–9

Contents lists available at ScienceDirect

Energy

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

Energetic and exergetic analysis of a new compact trigeneration system run with liquefied petroleum gas

Nestor Proenza Pérez*, Marlene Titosse Sadamitsu, Jose Luz Silveira, Julio Santana Antunes, Celso Eduardo Tuna, Atilio Erazo Valle, Natalia Faria Silva

São Paulo State University, Faculty of Engineering at Guaratinguetá, Department of Energy, (LOSE) Laboratory of Optimization of Energy Systems, Brazil

A R T I C L E I N F O

Article history:
Received 10 February 2015
Received in revised form
22 June 2015
Accepted 23 June 2015
Available online xxx

Keywords:
Cogeneration
Energetic
Exergetic
Internal combustion engine
Efficiencies

A B S T R A C T

In this study, the first and second laws of thermodynamics are used to analyze the quantity and quality of energy in a small compact trigeneration system. This combined cycle is composed of a little reciprocating ICE model GM, 1.0 CORSA (internal combustion engine), using LPG (liquefied petroleum gas) as fuel, HE1 and HE2 (two heat exchangers) and an AM (absorption machine) using ammonia–water as working fluid mixture. The mass and energy balance equations of the engine and subsystems are reviewed in detail. Exergy of each involved stream is calculated and the exergetic balance of each subsystem is presented, as well as the global system, identifying where and why losses and irreversibilities occurs. Efficiencies based on the second law of thermodynamics are calculated for each subsystem and compared. Special attention is given to identification and quantification of second law efficiencies and the irreversibilities of various processes and subsystems. The determination of the irreversibilities in each subsystem is particularly important since they are not identified in traditional first law analysis. Furthermore, this study revealed that the combustion was the most important contributor to the system inefficiency representing 36.0% of the total exergy input and 73% of the total exergy destruction. The exergetic efficiency of the trigeneration system is determined to be 51.19%.

1. Introduction

The Cogeneration Systems or CHP (Combined Heating and Power) and trigeneration or CCHP (Combined Cooling Heating and Power) as well known, are technologies with a rapid growth due to the ability to solve power supply problems more efficiently, economical and less polluting to the environment than those traditionally known and used for power supply and energy separately [1]. Cogeneration and trigeneration may be defined as the simultaneous production of electrical or mechanical energy and useful thermal or cooling energy from a single energy source, such as oil, coal, natural or liquefied gas, biomass, or solar as per Sonar et al. [1] and Silveira et al.[2]. These two technologies main objective is that most of the energy contained in the fuel is used, instead of only a small part. Thus, a more economical method is obtained compared to the systems where electricity and heat are separately produced. The efficiency of energy production can be increased from current levels that vary from 35% to 55% in the conventional power plants to over 80% in the CHP and CCHP systems [3].

In Brazil there is a large potential for the use of CHP and CCHP systems especially in the industrial sector according to Soares et al. [4]. In recent years the Brazilian government has encouraged the use of such technologies based on international experiences of countries like France, the UK, Denmark, Finland, the Netherlands and the US where incentive policies were created for fossil fuels and renewable sources use. In Brazil was created in the year 2000 the Cogeneration Incentive Program through Edict 212/2000, with a short term objective to provide private investment incentives in CHP systems providing enhanced thermoelectric generation capacity installed in the country [5]. Later in the year 2002 was created the Incentive Program for Alternative Sources of Electric Energy (PROINFA) by Law 10,438 to stimulate the electricity generation from renewable energy sources such as wind, biomass, and hydric, where the use of cogeneration systems associated with these systems is promoted through public financing incentives available in the Brazilian Development Bank (BNDES), direct subsidies, including taxes and import fees reduction cogeneration

* Corresponding author. Tel.: +55 12 3123 2239.
E-mail address: nestorproenza@yahoo.es (N. Proenza Pérez).

http://dx.doi.org/10.1016/j.energy.2015.06.094
0360-5442/

Nomenclature

$\dot{m}$	mass flow rate [kg/s]
T	temperature [K]
H	specific enthalpy [kJ/kg]
S	specific entropy [kJ/kg]
Q	heat [kW]
W	work [kW]
A,B,C,D	heat capacities constant
R	universal gas constant [J/mol K]
E	specific exergy [kJ/kg]
X	molecular fraction
Cp	average specific heat [kJ/kg K]
E	total exergy [kW]
LHV	low heating value [kJ/kg]

Subscript

in	input
out	output
i	any component
vc	control volume
ex	exhaust gas
0	reference condition
am	arithmetic mean
eff	effective
th	thermal
T	total
ch	chemical
u	net work
cw	cool water
HE	heat exchanger
AM	absorption machine
dest	destroyed
gen	generation

Superscript

n	Enesimo

Greek symbols

Ψ	degree of thermodynamic perfection
ξ	rational efficiency
η	energy efficiency
Ø	Coefficient

equipment as well as the guarantee of long-term contracts and attractive selling prices for cogeneration companies [6].

Several works have presented compact cogeneration and trigeneration systems based on internal combustion engine for production of heat and power. Giani Bidini et al. [7] report exergetic analysis in the new type cogeneration plants. This new plant is a combination of two interconnected combined heat and power systems: a reciprocating internal combustion engine cogenerator as the topping cycle and a Rankine cycle cogenerator which operates as the bottoming cycle on the exhaust gases from the ICE. The electrical and energetic efficiencies were 35.1% and 44.9% respectively, while the exergetic efficiencies it was 39.9%. The study of the small compact cogeneration system with an absorption refrigeration system working with different fuels as hydrated ethanol, diesel oil and natural gas is reported by Ref. [8], the comparative technical-economical analysis is made. Another work report for Rosen et al. [9] using a cogeneration system in the district energy systems in the city of Edmonton, Canada, realized the energetic and exergetic analysis considered three possibilities for the provision of central chilling services: electric chillers, single-effect absorption chillers and double-effect absorption chillers. The energetic analysis results reporting efficiencies vary significantly from 83 to 94%, however exergetic efficiency values were almost equal varying between 28 and 29%. R. E. Klaassen and M. K. Patel [10], performs a technical economic assessment of CHP systems working with natural gas related to district heat, estimating the primary energy savings through different methods compared to traditional systems, similar work is reported by Chunhui Liao et al. [11] but using coal as fuel. The combination of fuels such as H_2 and natural gas in residential CHP systems is reported by Gianluigi Lo Basso et al. [12], showing that the overall electrical efficiency increases with the mixture but the total thermal power decreases. Optimization studies in the field of trigeneration systems are reported by P. Arcuri et al. [13] and A. Piacentino et al. [14] where using different mathematical models, simulate the best plant design in technology terms, size, and operation time defining the best operating strategy to be employed.

Based on our search in the open literature the CHP and CCHP technologies are widely known and studied especially when they use natural gas as the primary fuel however there are not many papers with this reported system using LPG (Liquefied Petroleum Gas). The main objetive of this study is precisely the first and second Law of thermodynamics use to analyze the energy quantity and quality of a small trigeneration system consisting of a four-cylinder, with MPFI – Delphi system injection spark engine using LPG as fuel.

An estimation done by the PDE (Ten year Expansion Plan) [15] expects that over the next 10 years Brazil will experience an extraordinary oil production expansion due to the large investment in this sector (offshore production) about to triple its production from 2.1 million barrels per day in 2010 to 6.1 million barrels per day in 2020, the creation of new refineries will help increase the LPG production, covering domestic demand fully, even to export this derivative [16]. As the studies that aim to use this energy vector are of vital importance today.

2. Liquefied petroleum gas as fuel

LPG (Liquefied petroleum gas) was first put into use as an internal combustion engine fuel in the 1930s when a vehicle was first run on LPG in the eastern coast of the USA. Due to its good performance, interest was created among researchers to introduce it in a larger scale as an alternative/supplement to gasoline.

The use of LPG as alternative fuel to gasoline is common practice in spark ignition engines. While the main driving force for LGP use remains low cost, is usually less expensive than gasoline, to the end user, and its favorable pollutant emissions (they are less using LPG instead of gasoline), can produce quantities significantly less than some harmful emissions, in particular greenhouse gas carbon dioxide, probably it will be in the medium term, increase interest in LPG as fuel of the IC engine.

Although LPG fuel is used with new generation conversion systems in spark ignition engines, a little reduction in power output of engine occurs. The reason for this reduction is the decrease in the volumetric efficiency of the engine as the result of using LPG which expands 230–267 times while passing to the gas phase from liquid