Energy 56 (2013) 39–45

Contents lists available at SciVerse ScienceDirect

Energy

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

Thermoeconomic optimization for green multi-shaft gas turbine engines

Yousef S.H. Najjar*, Suhayb Al-Absi

Mechanical Engineering Department, Jordan University of Science and Technology (JUST), Irbid, Jordan

ARTICLE INFO

Article history:
Received 6 September 2012
Received in revised form
10 April 2013
Accepted 12 April 2013
Available online 29 May 2013

Keywords:
Thermoeconomic optimization
Gas turbine arrangements
Off-design performance
Green technology

ABSTRACT

The thermoeconomic analysis of a gas turbine engine with two turbines is presented and discussed in this work. Two configurations (in parallel and series free turbine) are presented and analysed. The thermoeconomic analysis relies on the energy and exergy analysis of the system, and the capital cost evaluated for each component using annualized capital cost equations. Then it is used in combination with exergy analysis to evaluate the net work and cost rate.

Optimization is performed by considering pressure ratio, turbine inlet temperature and cost as the important operating variables. The results are obtained for both configurations and represented in graphs and tables, the results are discussed and compared to each other.

The comparison of the two configurations shows that the specific cost (cost per kW) is higher for parallel than series (by 4%). However, the series has higher total cost than the parallel (by 7%).

1. Introduction

Thermoeconomics combines a thermodynamic (exergy) analysis with economic principles to provide the designer or operator of an energy-conversion system with information which is not available through conventional thermodynamic and economic evaluations. Hence it is crucial to the design and operation of cost-effective systems [1]. Energy efficiency could be obtained by different methods, among which is waste-heat recovery [2], combined cycles [3], using energy storage for peak shaving and load levelling [4] and in the limit widening the range of fuel specifications to improve thermoeconomics [5]. Thereby, contributing towards the green power generation [6].

Complete thermoeconomic analysis consists of exergy analysis, economic analysis, exergy costing and thermoeconomic evaluation [7]. Those steps are discussed comprehensively in a number of publications [8].

The rapid development of new cycles based on gas turbine technology in the last few years evinces imposed the importance of a complete thermoeconomic analysis. The complete analysis shows the influence of the most important cycle parameters and the economic boundary conditions during the design phase of advanced systems. A thermoeconomic approach may be used to solve this problem. In fact, thermoeconomics is a technique, which combines thermodynamic analysis directly with economic aspects in order to optimize thermal systems like a gas turbine based cycles. An introduction to the use of availability (exergy) and economics to optimize the design and operation a thermal systems was presented by M.J. Moran and H.N. Shapiro [9], and a detailed description for its application for the energy conversion systems was presented by El Sayed [10].

In this work, the main objective is to combine the exergy and energy analyses performed with economic analysis and evaluation of the specific cost (cost per kW) for each configuration. It is specifically intended to find out the optimum pressure ratio and turbine inlet temperature corresponding to minimum cost for major performance parameters (work, SFC and efficiency) and hence the green gas turbine power contribution. Optimal energy systems having a cost objective function have been the target of many researchers, El-Sayed, Evans [11] and Frangopoulos [12] are among the major contributors.

2. Plant description

The simple cycle gas turbine consists of a compressor, combustion chamber and turbine which are mechanically coupled to the compressor (Fig. 1).

In this work, the gas turbine plant studied has a compressor in which air is compressed from atmospheric pressure and delivered to two turbines arranged in two different configurations:

* Corresponding author.
E-mail address: y_najjar@hotmail.com (Y.S.H. Najjar).

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.04.016

Nomenclature

c	cost rate, \$/s
C	cost per unit exergy, \$/kJ
E	annualized purchased equipment cost, \$/y
E_r	annual capital cost, \$/y
FCR	annual fixed charge rate
HV	lower heating value of the fuel, kJ/kg
m	mass flow rate, kg/s
p	Pressure, bar
SOFC	solid oxide fuel cell
T	temperature, K
TIT	Turbine inlet temp. (Combustor outlet temp.)
W	work rate, W
X	exergy rate, W
Z	capital cost rate of equipment, \$/s
Greek letters	
H	efficiency
ψ	specific exergy, kJ/kg
Φ_r	maintenance factor
Subscripts	
a	ambient, air
c	compressor
Cc	combustion chamber
g	gas
N	net, number of operating hours/y
t	turbine
0	environment

1. Parallel: where the combustion gases expand to atmospheric pressure in both turbines, one turbine drives the compressor, to which it is mechanically coupled CT, while the other develops the power output of the plant PT (Fig. 2).

2. Series: where the combustion gases expand through the first turbine which drives the compressor *CT*, then reheated and expanded to atmospheric pressure in a free power turbine which develops the power output of the plant *PT* (Fig. 3).

Each turbine in the two configurations has its own combustion chamber; the fuel supply to each can be controlled independently.

3. Theoretical cost analysis of gas turbine components

The method used here for the thermoeconomic analysis is based on the exergy analysis. The approach to this method is described in details by El-Sayed in two publications, for the methodology [13] and the applications [14].

3.1. Compressor (Fig. 4)

Cost balance:

$$\dot{C}_2 = \dot{C}_1 + \dot{C}_{W_c} + \dot{Z}_c \tag{1}$$

$$c_2\dot{X}_2 = c_1\dot{X}_1 + c_{W_c}\dot{W}_c + \dot{Z}_c$$

where, c: cost per unit exergy [\$/kJ]; c_{W_c}: cost per unit exergy of consumed work by compressor [\$/kJ]; $\dot{W}_c$: power consumed by compressor [kW].; $\dot{Z}_c$: operating and owning cost of the compressor [\$/s].

Rewriting the equation above,

$$c_2 = \frac{c_1\dot{X}_1 + c_{W_c}\dot{W}_c + \dot{Z}_c}{\dot{X}_2}$$

3.2. Combustion chamber (Fig. 5)

Cost balance:

$$\dot{C}_2 = \dot{C}_1 + \dot{C}_f + \dot{Z}_{cc} \tag{2}$$

$$c_2\dot{X}_2 = c_1\dot{X}_1 + c_f\dot{X}_f + \dot{Z}_{cc}$$

where, c_f: cost per unit exergy of fuel [\$/kJ]; $\dot{Z}_{cc}$: operating and owning cost of the combustion chamber [\$/s].

Rewriting the equation above,

$$c_2 = \frac{c_1\dot{X}_1 + c_f\dot{X}_f + \dot{Z}_{cc}}{\dot{X}_2}$$

3.3. Turbine (Fig. 6)

Cost balance:

$$\dot{C}_1 + \dot{Z}_t = \dot{C}_2 + \dot{C}_{W_t} \tag{3}$$

$$c_1\dot{X}_1 + \dot{Z}_t = c_2\dot{X}_2 + c_{W_t}\dot{W}_t$$

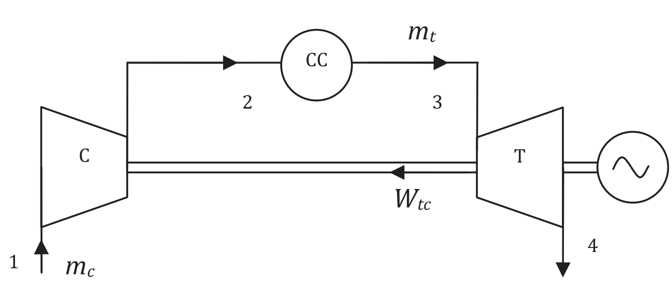

Fig. 1. Simple configuration.

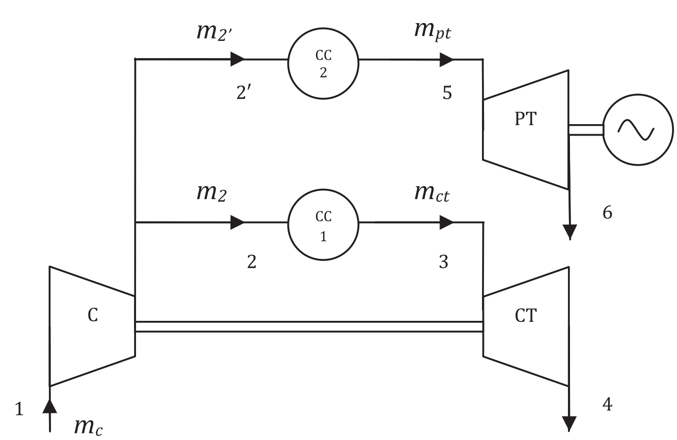

Fig. 2. Parallel configuration.