EXERGO-ECONOMIC OPTIMIZATION FRAMEWORK FOR BIOGAS FUELLED GAS TURBINE AT DESIGN POINT

HASAN BARZEGARAVVAL

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Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

Dedicated to my father and mother.

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ABSTRACT

Energy system optimization is the first step to address global warming, even for renewable sources like biogas. Optimization is necessary for efficient yet economic resource utilization, which has been a wide study area. However, no comprehensive general framework is proposed for optimization, mainly resolving the optimal point selection issue. This study aimed to provide a framework for exerting economic optimization of biogas fed systems and applying it to specific gas turbines. The proposed model in this research includes all steps from problem setup to final optimal point selection. A genetic algorithm was applied to obtain the Pareto front, and objective functions were evaluated by thermodynamic modeling of the system. A set of dimensionless parameters were introduced that smoothly defined the correlation between all design variables (decision variables) and optimal objectives (total cost and exergy efficiency). Then correlations between design parameters and optimal design variables were evaluated using meta functions of fourth-order. In this study, the design variables were compressor pressure ratio, gas turbine and compressor isentropic efficiencies, turbine inlet temperature, and preheater outlet temperature. Design parameters were cost of fuel, net power, and fuel methane content. To achieve a general optimal solution, a fuel costing approach based on the fuel exergy was proposed. The new costing approach allows disintegration and elimination of the fuel processing while accounting for the effect of the processing on the cost of fuel which allowed a general solution for the optimal gas turbine. A design problem was solved using the developed framework. Results of the design problem showed that the minimum cost ratio (*cr*) of 3.0 with minimum specific emission of 0.4962 kg/kWh. If *cr* increases to 3.5, the minimum specific emission will reduce to 0.4534 kg/kWh. The results demonstrate that the proposed framework is able to provide an optimal solution for a variety of CO_2 emission levels, cost, and financing considerations where this optimization was not possible to determine by the previous approach.

ABSTRAK

Pengoptimuman sistem tenaga ialah langkah pertama untuk menangani pemanasan global, walaupun untuk sumber boleh diperbaharui seperti biogas. Pengoptimuman adalah perlu untuk penggunaan sumber yang cekap lagi ekonomi, yang telah menjadi bidang pengajian yang luas. Walau bagaimanapun, tiada rangka kerja umum yang komprehensif dicadangkan untuk pengoptimuman, terutamanya menyelesaikan isu pemilihan titik optimum. Kajian ini bertujuan untuk menyediakan rangka kerja untuk melaksanakan pengoptimuman ekonomi bagi sistem suapan biogas dan mengaplikasikannya pada turbin gas tertentu. Model yang dicadangkan dalam penyelidikan ini merangkumi semua langkah dari persediaan masalah hingga pemilihan titik optimum akhir. Algoritma genetik telah digunakan untuk mendapatkan lengkung Pareto, dan fungsi objektif dinilai dengan pemodelan termodinamik bagi sistem. Satu set parameter tanpa dimensi telah diperkenalkan yang mentakrifkan dengan lancar korelasi antara semua pembolehubah reka bentuk (pembolehubah keputusan) dan objektif optimum (kos jumlah dan kecekapan eksergi). Kemudian korelasi antara parameter reka bentuk dan pembolehubah reka bentuk optimum dinilai menggunakan metafungsi tertib keempat. Dalam kajian ini, pembolehubah reka bentuk adalah nisbah tekanan pemampat, turbin gas dan kecekapan isentropik pemampat, suhu salur masuk turbin, dan suhu alur keluar prapemanas. Parameter reka bentuk adalah kos bahan api, kuasa bersih dan kandungan metana bahan api. Untuk mencapai penyelesaian optimum umum, pendekatan kos bahan api berdasarkan eksergi bahan api telah dicadangkan. Pendekatan kos baharu membolehkan pengasingan dan penyingkiran pemprosesan bahan api dengan mengambil kira kesan pemprosesan ke atas kos bahan api yang mana membolehkan penyelesaian umum untuk turbin gas optimum. Masalah reka bentuk telah diselesaikan menggunakan rangka kerja yang dibangunkan. Keputusan masalah reka bentuk menunjukkan nisbah kos minimum (cr) adalah 3.0 dengan pelepasan spesifik minimum 0.4962 kg/kWj. Jika cr meningkat kepada 3.5, pelepasan spesifik minimum akan berkurangan kepada 0.4534 kg/kWj. Keputusan menunjukkan bahawa rangka kerja yang dicadangkan mampu menyediakan penyelesaian yang optimum untuk pelbagai aras pelepasan CO_2, kos dan pertimbangan kewangan yang mana pengoptimuman ini tidak dapat ditentukan dengan pendekatan terdahulu.

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LIST OF ABBREVIATIONS

AD	-	Anaerobic Digestion
AP	-	Air Preheater
BM	-	Bio Methane
BNS	-	Bio Methane No Supporting intensive
BS	-	Bio Methane with Supporting intensive
CC	-	Combustion Chamber
CCHP	-	Combined Cooling Heating and Power
CHP	-	Combined Heat and Power
CMP	-	Carbon Mitigation Pricing
DOE	-	Department Of Energy (USA)
GA	-	Genetic Algorithm
GHG	-	Green House Gas
GT	-	Gas Turbine (cycle or component)
IC	-	Internal Combustion (engine)
IRR	-	Internal Rate of Return
LHV	-	Lower Heating Value
MGT	-	Micro Gas Turbine
NCMP	-	No Carbon Mitigation Pricing
NPV	-	Net Present Value
NPVR	-	Net Present Value Ratio
NRCS	-	National Renewable Cost Survey
NREL	-	National Renewable Energy Lab (USA)
O&M	-	Operation and Maintenance
ORC	-	Organic Rankine Cycle
PAD	-	Pressurized Anaerobic Digestion
PECC	-	Plant Exergo-economic Characteristic Curve
ROI	-	Return Of Investment
SOFC	-	Solid Oxide Fuel Cell
TIT	-	Turbine Inlet Temperature

LIST OF SYMBOLS

a	-	Constants
A	-	Area(m^2) or equation constants
AV	-	Annualize value
b	-	Cost functions' constants
$\dot{C}$	-	Cost rate($/S)
c	-	Cost per exergy ($/kW)
Cap	-	Capacity or size of system
CF	-	Cash flow
$\overrightarrow{Cp}$	-	Vector of heat capacities
cr	-	Product to fuel costs ratio
CR	-	Fixed to current costs ratio
DV	-	Vector of decision or design variables
E	-	Emission of CO_2 (kg)
e	-	Emission of CO_2 per unit of product (kg/kWh)
ex	-	Exergy per unit of mass (kJ/kg)
$\dot{Ex}$	-	Exergy rate (kW)
FV	-	Future value
h	-	Enthalpy
i	-	Interest rate
$\dot{m}$	-	Mass flow rate (kg/s)
$\overrightarrow{M}$	-	Molar mass vector
$\dot{n}$	-	Molar rate
N	-	Operating hours (hr/year), or number of reactive carbons
P	-	Pressure (bar)
PV	-	Present value
$\dot{Q}$	-	Heat transfer rate (kW)
R	-	Gas constant
r	-	Pressure ratio
s	-	Entropy (J/mol-°K)

T	-	Temperature (ºK)
U	-	Heat exchanger
$UCRF$	-	Uniform capital recovery factor
v	-	Specific volume(m^3/kg)
V	-	Velocity(m/s)
w	-	Specific work (kJ/kg)
$\dot{W}$	-	Power (kW)
x	-	Mole fraction
X	-	Methane mole fraction
$\vec{X}$	-	Mole fraction vector
$\vec{Y}$	-	Vector of design parameters
$\dot{Z}$	-	Purchase (fix) cost rate ($/s)
Z	-	Compressibility factor

Greek Letters:

α	-	Pressure drops , or change rates parameters
β	-	Exergy to LHV ratio, or chemical to physical exergy ratio
η	-	Efficiency
φ	-	Operation and maintenance cost correction factor

Subscripts:

0	-	Dead state
*	-	Dimensionless star values
a	-	Air
AC	-	Air compressor
AP	-	Air preheater
ch	-	Chemical
D	-	Destruction
eco	-	Economic
el	-	Electrical
ex	-	Exergetic
f	-	Fuel
g	-	Gas
i	-	Index
is	-	Isentropic

k	-	Air heat capacity ratio
lm	-	Logarithmic mean
m	-	Mixture
net	-	Net output
OP	-	Optimal
p	-	Product
ph	-	Physical
r	-	Ratio
real	-	Actual or real
ref	-	Reference value
s	-	Specific
tot	-	Total value
W	-	Work
Z	-	Purchase or fix cost

Superscript

0		Value at standard condition , or formation
n	-	Years , or cost equation constant

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CHAPTER 1

INTRODUCTION

1.1 Problem background

"At today's Climate Ambition Summit, I appealed to leaders worldwide to declare a State of Climate Emergency in their countries until carbon neutrality is **reached".** UN secretary general, Antonio Guterres 12 December 2020.

Long-time debuted global warming is the state of emergency now and carbon neutrality is not a classy dream but a must.

Despite astonishing advances in renewable energy and carbon emission control technologies, there are still issues, including but not limited to, economic concerns of renewable and carbon neutrality projects. Either the energy source or the technology is expensive. In fact, the economic consideration is a huge issue in marketing and globalising the green energy solutions and to achieve carbon neutrality and these concerns must be addressed. Methods like exergoeconomic optimization and analysis are developed to address this issue by considering the cost as well as efficiency to reach a feasible solution.

In addition to optimization, the price of energy source is affecting the cost of produced energy. Biogas is one of the interesting energy sources which is reasonably priced and carbon neutral. In fact, biogas from wastes is a source of methane which is ten time more dangerous than carbon dioxide and it is naturally produced from organic wastes. So, implementing biogas with exergoeconomic optimization delivers a feasible green solution.

However, when it comes to implement the exergoeconomic method on biogas fuelled systems, some issues are witnessed which must be addressed. The biogas comes from variety of sources and production methods which results in large variation of its composition and price. The pricing based on LHV, which is the common method, does not account the resource quality and fuel costing based on LHV is not a suitable approach.

The second problem which is faced after optimization is that the approach to find the optimal solution is not systematic and lacks generality. To the author's knowledge, there is no established framework for optimization which leads to a general solution on literatures.

The lack of suitable fuel pricing method, and a systematic approach to optimization especially in result interpretation are two problems which are observed, and this research is focused to address them.

1.2 Problem statement

Biogas is vastly diverse in source and composition. Though mainly consists of two components, carbon dioxide and methane, the mole fraction of the components is largely affected by the production method and source of biowaste which makes the pricing sophisticated. The LHV of the fuel is common method for pricing. However, when the LHV is reducing significantly, the physical condition of delivered fuel including its pressure become important as well. In this case, using LHV based fuel costing ignores other possible sources of physical exergy and results in inappropriate fuel costing method which affects the estimated cost of final product of the system.

The current fuel costing is not appropriate to achieve a general optimal solution. Firstly, the fuel costing is based on LHV which is inconsistent with the exergoeconomic evaluation. Secondly there are plenty of the biogas production and fuel processing units, which results in different costs of fuel. The change to fuel costing based on exergy allows to treat the fuel as a product of a topping process, and lead to a general solution. For all the processing types and units, the economic effect can be summarized in the fuel exergy cost.

1.2.1 Need for an optimization framework

The second problem is lack of systematic optimization framework. While there are many optimization studies, no framework is developed which delivers general and extendable optimization results as functions of design parameters. For example, if design parameters like fuel cost, system size (power demand) and fuel composition change, the optimization should be conducted again to obtain the optimal design and product cost.

A framework is a structured procedure. The optimization framework is the structured methodology of the optimization, which can be applied step by step to achieve the goal of optimization. On the exergo-economic optimization, that means the steps from the modeling to final optimal point evaluation.

The framework must include the step-by-step structured method to achieve the goal of optimization. However, there are some key points in considering the goal of optimization:

1- When considering the economy of the plan, the goal of optimization is not always the cost minimization. The investment cost, cost of emission and other factors are involved in making the final decision on what is the optimal cost.

2- The design parameters are susceptible to change that affects the optimal point.

3- For each optimal point, one set of design variables exists. If optimal point selection and design parameters change, optimal design variables also change.

The point expressed above affects the optimization outcome. Currently the optimization carried out in following steps in most of cases.

1- System model development.

2- Setting objectives and design variable.

3- Optimization is conducted.

4- The optimal point is selected. Most used method is equilibrium point which is a mathematical concept.

5- The optimal design variables are values for corresponding optimal point (objectives).

The main drawback of the mentioned approach is the optimal point selection. In most of the cases, the optimal point is selected using a method called equilibrium point which is a purely mathematical idea and does not represent any significant physical meaning.

In addition, the methods of the optimal point selection normally dismiss the fact that all points on pareto frontier are optimal [1]. Points on the pareto frontier are optimal costs at given efficiencies or optimal efficiencies at given costs [2&3]. Hence, any point on pareto frontier can be the candid of optimal design for certain criteria and selecting the point is not simply a mathematical procedure. So, optimization outcome should contain all points on pareto and point selection should be excluded.

1.3 Research goal

The goal of this research is to improve the exergoeconomic optimization technique in a way that it can be applied on a biogas system with fuel composition and cost variations. Also, the improved method should result in general solution which is interpretable by different teams involved in decision making.

1.4 Research objectives

The objectives of the research are:

1. To propose a new fuel costing method based on its' total exergy and analysis its' effects and compare it with LHV costing method to ensure its superiority.

2. To introduce new non-dimensional variables for emission, performance and decision variables that solve the scattered data issue. This is a critical objective that must be achieved, and it is the fundamental block of the framework.

3. To develop a new framework for optimization which correlates objectives and design parameters to achieve general solutions.

1.5 Scope of study

This study aims to develop an optimization framework for energy systems. However, the focus of the current work is on the exergo-economic optimization of biogas fueled gas turbine. The system under study is a gas turbine with net power output of 1 to 10 MW. This is an industrial range which is suitable for large biogas production plants. The focus is on the biogas fuel with main components of CO_2 and CH_4.

Though the fuel is biogas, emission factor is introduced to extend the generality of the framework to the cases which pure methane is added or, the carbon emission per unit of product is important even for biogas fuels.

Though the obtained framework is applicable in any optimization problem, but the obtained numeric data in this research is only applicable to gas turbines with biogas which is mainly consists of carbon dioxide and methane.

In the economic analysis of the current study, purchase cost of components, the O&M and fuel cost is considered. The target is to produce the most work with minimal cost of equipment and fuel. There is no carbon mitigation plan, tax intensives or other supportive green measures involve in the analysis. This research does not deal with any benefit or investment return measures like rate of return or net present value. It solely focused on the cost minimization. However, the obtained data is the foundation for the desired financial analysis.

The thermodynamic model of the system is carried out at design point. There is no off-design calculation as well as operation strategy optimization. The output is the best system design for given interest rate and biogas composition.

The scope of this study is not, the optimization of a single case study, but to develop a framework and methodology for optimization of energy systems. the implementation of the method is presented for a gas turbine optimal design.

In addition, it worth emphasizing that, the scope of the current work is limited to design point. Off design calculations and operation strategy optimization is not a part of the current work.

1.6 Significance of study

With increasing concerns over the carbon reduction and system optimization, a framework for exergo-economic optimization is a necessity. There should be an approach which provides general and extendable solutions with a systematic method to present and select the optimal point according to quantified and justified cost of product, emission, and investment cost.

In addition, the methods of data presentation which are proposed in this research solves the issue of scattered pattern in obtained optimal decision variables. The dimensionless form of variables defined in this study, provides a clear and smooth functionality between the design variables, objectives, and design parameters.

In addition, the fuel costing method proposed here is based on exergy and is a unified resource costing method which allows us to cost all resources on a basic merit of exergy delivered. This method of costing solves the issue of case-dependent optimization result. This makes the analysis more realistic, generic, and comprehend since it involves all the exergy flows and types which enter the system and produce the output.

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