Energy Conversion and Management 60 (2012) 180–187

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Sensitivity analysis applied to the multi-objective optimization of a MCFC hybrid plant

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ARTICLE INFO

Article history:
Available online 20 March 2012

Keywords:
Molten carbonate fuel cell
Lifetime analysis
Multi-objective optimization
Sensitivity analysis

ABSTRACT

In this paper, the multi-objective optimization of a molten carbonate fuel cell (MCFC) based hybrid plant fueled with landfill gas is performed. System operation is significantly affected by off-design conditions. These are due to variations methane concentration occurring as the landfill depletes, performance degradations of the components, particularly the fuel cell, and ambient conditions. For these reasons, the objective functions are defined considering the plant lifetime.

Some of the parameters affecting the results, as the voltage degradation, the cost of fuel cell, the methane concentration and the unit cost of landfill gas can be only estimated or forecasted and their actual values are uncertain. Therefore, the optimization is performed considering a sensitivity analysis in order to estimate the effects of possible variations on the Pareto front.

The following free design variables are considered: pressure and temperature operation of the MCFC, turbine inlet temperature, fuel mass flow rate. In addition, the optimal configuration of the heat exchanger network is selected for each set of the design variable.

1. Introduction

Biogas in the next future will represent a non-negligible energy resource. In Europe, it currently covers less than 0.4% of the primary energy consumption (landfill gas represents about 50% of the total biogas production), but the sustainable potential for 2020 is more than 2.5% [1]. High temperature fuel cells are particularly promising for electricity production from biogas [2,3], as they are able to improve the typical efficiencies of internal combustion engines. High efficiencies can be achieved with hybrid systems, obtained by integrating fuel cells with gas turbines [4,5]. The main drawbacks concern the high investment costs of these systems.

This paper is focused on the optimization of a landfill gas fueled hybrid system, which produces electricity and hydrogen. The system is defined "hybrid" because it is obtained by integrating three different subsystems: a microturbine, a molten carbonate fuel cell (MCFC) section and a pressure swing absorption system (PSA) for hydrogen production. Each subsystem is constituted of various components, which are described in the next section. Components are modeled considering design and off-design conditions.

The objective of this paper is the optimal design of the entire system. Optimization involves the selection of the configuration of the heat transfer network and the value of the main design parameters. The optimization of hybrid systems is conducted in various papers available in the literature. In [3] the multi-objective optimization of a biogas fueled hybrid system obtained by integrating a MCFC and a microturbine is performed. A single design point is considered, but changes in the performances due to cell degradation are considered. In [6], a molten carbonate fuel cell (MCFC) and a gas turbine are thermally integrated to obtain a hybrid system. The system is then optimized by varying the fuel cell size and the fuel utilization coefficient. In [7], the optimization of plant configuration (synthesis) and the design optimization of a hybrid SOFC-gas turbine is performed. The optimization is obtained by applying a genetic algorithm followed by gradient basis algorithm. The design point corresponding to the minimum cost is obtained. In [8], a multi-objective optimization of a natural gas fueled SOFC-micro-gas turbine considering minimum cost and maximum efficiency is performed. The optimal heat integration is obtained by using pinch analysis, which means that the heat transfer structure is modified during the optimization process. In [9], a solid oxide fuel cell and intercooled gas turbine (SOFC–ICGT) hybrid cycle is considered. The optimal design is investigated by applying a design of experiment technique. Four free parameters are considered in the optimization: moisture content in the gas out of the humidifier, excess air, overall pressure ratio, low pressure compressor pressure ratio. In [10], a SOFC/GT system with CO_2-capture is optimized using genetic algorithms. The system structure is considered as fixed, while six design parameters are considered: pressure ratio, reformer duty, cell voltage, air inlet

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doi:10.1016/j.enconman.2012.02.011

Nomenclature

A	heat transfer area (m^2)
A	annuity (€/year)
c	unit cost (€/kJ)
c	specific heat (kJ/kg K)
C	investment cost (€)
E	reversible potential (V)
G	mass flow rate (kg/s)
h	annual operating hours (h/year)
H_i	lower heating value (kJ/kg)
i	interest rate
j	current density (A/m^2)
K	equilibrium constant
m	mass flow rate (kg/s)
n	rotational speed (r/min)
n	lifetime (year)
NTU	number of transfer units
p	pressure (Pa)
R_{tot}	irreversibilities at the anode, cathode and electrode (Ω)
t	operating time (h)
T	temperature (°C)
U	global heat transfer coefficient (kW/m^2 K)
W	power (kW)
y_i	molar fraction of the species i
Z	investment cost rate (€/s)

Greek

β	pressure ratio
ε	electrical efficiency
ε	effectiveness
Φ	heat flux (kW)
η_{ne}	Nerst loss (V)

Subscripts

c	compressor
D	design condition
el	electrical
GT	gas turbine section
HE	heat exchanger
l	landfill gas
MCFC	molten carbonate fuel cell
t	turbine

temperature in the stacks, fuel mass flow rate, supplementary fuel mass flow rate and air mass flow rate.

In the present paper, a multi-objective optimization, considering minimization of the unit cost of electricity and maximization of electrical efficiency, is performed. These quantities are evaluated along the plant lifetime, in order to account for the effect of fuel cell degradation and variations in landfill gas composition and ambient temperature. In addition, appropriate distributions of the uncertainties associated to the operation variables are obtained on the basis of experimental data or information from the literature. The effect of these uncertainties on the Pareto front of the optimal designs is considered.

2. System description

Fig. 1 shows a schematic of the hybrid system. Starting from the microturbine, an air mass flow (flow 25) enters the air compressor (*C*) to be compressed up to about 4 bar (flow 24). This flow is split in two streams. The first stream (flow 21) goes to the gas turbine system and the second one (flow 13) goes to the MCFC cathode. Flow 21 is heated in the recuperator (flow 22) by means of the exhausts (flow 20) exiting the gas turbine (*T*) and then enters the combustor (*CC*) together with the fuel flow. The combustion gas (flow 23) enters the turbine where it expands. After the recuperator, it is mixed with flow 16 (exhaust cathodic flow) and used in the evaporator, where water (26), coming from the cooler 2, evaporates.

The steam produced in the evaporator (flow 2) is mixed with landfill gas. The resulting flow (3) is heated in the heat exchanger, where the flow coming from reformer (5) provides the necessary heat to perform the transformation 3–4. After that, flow 4 enters the reformer where the steam reforming reaction and water gas shift reaction occur. Flow 6R is divided in 6A (to cooler 1) and 6 (to anode). The latter goes out from the anode (7) and burns in the catalytic burner (CB) after mixing with flows 7A (from the cooler 1) and 12 (from the cathode).

The combustion gas (9) is mixed with the air flow from the air compressor (13) and feeds the cathode. The stream which exits the cathode (11) is partially recirculated to the CB-cathode (12). The other portion (flow 14) returns to the evaporator (16) and the combustor (15).

Flow 6A, after being cooled down in the two coolers (28), flows in the water–gas shift reactor and to the condenser. The flow 30 is compressed and taken in proper condition (31) for the hydrogen separation in the pressure swing absorption system (PSA). Here, some hydrogen is extracted and stored, while the remaining flow (32) is heated in the cooler 1 and mixed with the outgoing anodic flow.

3. System model

A steady-state black box model of the main components (MCFC, reformer, catalytic burner, heat exchangers, PSA) is used for preliminary design and design improvement. The model is built in Engineering Equation Solver (EES). Each flow is considered as the summation of seven different chemical species: CH_4, CO, CO_2, H_2O, N_2, O_2, H_2. These are considered as ideal gases except for pure water, which is modeled using the Martin-Hou equation for real fluids.

The model of the electrochemical phenomena inside the fuel cell is based on the polarization curve:

$$V_0 = E - \eta_{ne} - jR_{tot} \tag{1}$$

where E is the reversible potential, η_{ne} is Nerst loss, j is current density and R_{tot} is the summation of irreversibilities occurred at the anode, cathode and electrode. Resistances have been calculated from the expressions available in [11].

Voltage degradation depends on time and the fuel cell operating temperature (T_{MCFC}). This is modeled using the following expression, which has been derived from measured data available in the literature [13,15]:

$$V = V_0 - (9.8 \times 10^{-20} \cdot e^{0.047 \cdot T_{MCFC}}) \cdot t \tag{2}$$

where t is the operating time in hours.

The electrochemical reactions taking place on the cathode side and the anode side are considered.

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{3}$$

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \tag{4}$$

In addition, the water–gas shift reaction (WGS) is considered at the anode side.