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Performance assessment of Molten Carbonate Fuel Cell–Humid Air Turbine hybrid systems

R. Chacartegui *, M.J. Blanco, J.M. Muñoz de Escalona, D. Sánchez, T. Sánchez

Thermal Power Group, Department of Energy Engineering, University of Seville, Seville, Spain

HIGHLIGHTS

- ▶ Molten Carbonate Fuel Cell (MCFC) cost reduction is required.
- ▶ Not reached with standalone MCFCs or gas turbine-MCFC hybrid systems.
- ▶ Humid Air Turbine improves gas turbine performance with reduced cost.
- ▶ An hybrid system MCFC–HAT cycle could reduce the generation cost.

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ABSTRACT

One of the most promising technologies for stationary power applications is the Molten Carbonate Fuel Cell (MCFC). This is due to its high efficiency, low emissions and the medium–high operating temperature. This high temperature allows for hybridization with other power generation technologies where the bottoming cycle recovers part of the heat in the fuel cell exhaust stream, hence resulting in highly efficient hybrid systems. The current MCFC hybrid system designs use microturbines as bottoming cycle.

This paper presents the integration of a MCFC with a bottoming Humid Air Turbine (HAT) instead of the conventional microturbine. The HAT cycle, even if still under development, provides a relatively simple and inexpensive solution to increase the power output of the microturbine. An indirect integration between the MCFC and the HAT cycle is chosen aiming to simplify the layout and operation of the new system and considering that the necessary modifications to be performed in the microturbine are relatively simple (and therefore the additional equipment is expected to be relatively economical).

The results presented in this paper show the potential of this MCFC–HAT combination with an increase of the net power output of 6 percentage points and an efficiency increase of 3 percentage points from the high efficiency conventional hybrid system (MCFC–MGT). An economic analysis as function of the MCFC investment cost is presented showing a break-even-cost of 2092 €/kW improving the estimated for the MCFC–MGT.

1. Introduction

The steadily escalating oil prices and stricter environmental regulations concerning the emissions of contaminants have set the focus on developing new technologies for cleaner and more efficient power production systems. One of these promising technologies for stationary applications is the Molten Carbonate Fuel Cell (MCFC).

MCFCs present unmatched characteristics in the low and medium power output range, with stand-alone efficiencies in the range of 45–55% [1–5] as shown by several plants already operating in US and Korea [6,7]. A number of research works [8–13] have also explored the potential of hybrid system based on the combination of gas turbines and MCFCs, showing that efficiencies of up to 67% for a pressurized MCFC in combination with a gas turbine [8] is to be expected. MCFCs have nevertheless the main challenge of reducing the installation cost (€/kWe) to be fully competitive against other well established technologies, a target that can be achieved by either reducing the manufacturing cost or increasing the power output of the system. In this latter regard, the performance of MCFC-based hybrid systems can be enhanced by the smart combination of these systems with bottoming Humid Air Turbines (HAT cycles), bringing about higher efficiency at very limited capital cost.

The HAT cycle was originally patented by Rao [14], with further improvements given in [15]. It is based on the recuperation of a fraction of the waste heat carried by the exhaust gases of a gas turbine in order to generate hot water, in a series of heat exchangers, which is later injected in a saturator where the pressurized air

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* Corresponding author. Tel.: +34 954467615; fax: +34 954487243.
E-mail address: ricardoch@us.es (R. Chacartegui).

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Nomenclature

A	area (m^2)
B	pump
C	heat capacity (W K^{-1})
Cp	specific heat at constant pressure (J kg^{-1} K^{-1})
E	potential (V)
EES	Engineering Equation Solver
ECO	economizer
F	Faraday constant (96,485 C)
f	enhancement factor
G	Gibb's free energy (J kg^{-1})
h	enthalpy (J kg^{-1})
HAT	Humid Air Turbine
HTHX	high temperature heat exchanger
HX	heat exchanger
IRR	internal rate of return
j	current density (A m^{-2})
K	chemical reaction constant
LCOE	levelized cost of electricity
$\dot{m}$	mass flow (kg/s)
MCFC	Molten Carbonate Fuel Cell
MIX	mixer
MUW	make up water
$\dot{n}$	molar rate (mol s^{-1})
p	pressure (bar)
PR	pressure ratio (–)
$\dot{Q}$	heat (W)
r	expansion ratio
R	ideal gas constant (J mol^{-1} K^{-1})
Re	resistance (Ω m^2)
REG	regenerator
S	water separator
SAT	saturator
STCR	Steam To Carbon Ratio (%)
T	temperature (K)
TIT	turbine inlet temperature (K)
TET	turbine exhaust temperature (K)
U_{H2}	fuel utilization factor (%)
U_{CO2}	carbon utilization factor (%)
V	voltage (V)
$\dot{W}$	power (W)
x	molar fraction (–)

Greek letters

γ	heat capacity ratio (–)
η	efficiency (%)
ε	efficiency (%)

Superscripts and subscripts

°	standard ideal conditions, design conditions
air	air
an	anode
ca	cathode
eq	equilibrium
in	inlet flow
ir	internal resistance
p	polytropic
out	outlet flow
oxid	oxidation reaction
ref	reference state
s	isentropic
sat	saturator, saturation conditions
shift	shift reaction
t	turbine
vap	vaporization

delivered by the compressor is humidified. The increased expansion mass flow raises the power generated by the turbine, therefore increasing the power output and efficiency of the cycle. Different works analyze the performance of this cycle [16–23] and, even if there are studies for large-scale power generation [17,24], its great potential lies on the distributed power generation market with low and mid power output applications. This is the scenario where the lower initial investment, reduced NO*x* emissions, lower transmission losses and system compactness make it a preferred choice with respect to conventional technologies. Pilot installations that make use of a HAT cycle can be found today in Lund, Sweden [19, 20], where a 600 kW power plant has been built, and in Hitachinaka City, Japan, where a 3 MW plant has been developed by Hitachi [25]. An experimental facility focused on the saturator performance is found in Genoa, Italy [16].

The feasible applications of a HAT cycle are diverse. Its direct application is to improve the performance of stand-alone gas turbines. Nevertheless, the closed HAT cycle has been proposed for applications that make use of external heat sources like solar energy [26], solid fuels (for instance coal [27]) and even in integrated gasification plants [28]. In the distributed generation sector, they have also been proposed to be used in combination with a Solid Oxide Fuel Cell (SOFC) whose waste heat serves as heat source for the HAT turbine [29,30]. In this SOFC hybrid cycle, Rao et al. [29,30] reported potential efficiencies as high as 66.2–76% depending on the composition and systems integration. The results presented for that integration showed Levelized Costs of Electricity (LCE) and capital costs which were 4% lower than for the conventional SOFC and gas turbine hybrid scheme. In the same line, Kuchonthara et al. [31] simulated a hybrid system based on a SOFC in combination with a HAT cycle obtaining overall efficiencies ranging from 60% to 67% for pressures varying from 5 to 15 bar.

Regarding MCFC-based hybrid systems, Ubertini and Lunghi [32] studied a MCFC operated at ambient pressure and combined with a STIG cycle, reporting that efficiencies as high as 69% were attainable.

The goal of this paper is to analyze the potential of a hybrid system based on a topping MCFC and a bottoming HAT cycle. To this aim, an indirect integration of both systems where the gas turbine is externally heated by the MCFC exhaust gases, by means of a high temperature heat exchanger, has been selected. It is worth noting that though this indirect integration is expected to yield lower efficiencies than a direct type (in which the fuel cell is boosted by the compressor), it allows a simpler integration, faster startup and easier operation of the system. Additionally, the stack costs are reduced in comparison with the pressurized stack [33]. Based on a reference 500 kW (gross) MCFC, the HAT cycle is derived from an existing microturbine; in this sense, it is worth noting that microturbines operating with steam injection have already been studied in the public domain [34,35]. The HAT cycle has been chosen for the bottoming cycle, even if still under development, because it provides a relatively simple and inexpensive solution to increase the power output of a microturbine. For the layout chosen in this work, application and power range, the extra equipment to be added to an existing recuperative microturbine would be a saturator, a heat exchanger and two pumps.

The use of this HAT cycle is expected to improve the overall efficiency yielded by other conventional MCFC-based systems,