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Optimization of the working cycle for a hydrogen production and power generation plant based on aluminum combustion with water

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ABSTRACT

The working cycle of a novel hydrogen and power generation system based on aluminum combustion with water is analyzed in order to evaluate the best performance in terms of energy conversion efficiency. The system exploits the exothermic reaction between aluminum and steam and produces thermal power for a super-heated steam cycle and hydrogen as a by-product of the reaction.

A lumped and distributed parameter approach is adopted for simulating the whole thermo-dynamics cycle and it includes the main components such as the combustion chamber, the steam generator, the turbine and the heat exchangers. Proper numerical models are created to account for the physical phenomena occurring in each of the considered component and are validated against experimental measurements available in literature or theoretical formulations.

In particular several plant configurations corresponding to different working cycles are investigated, and their performance in terms of global efficiency, power output and hydrogen yield is discussed. The adoption of a turbine back pressure working cycle demonstrates to reduce the aluminum consumption and to enhance the electrical power conversion efficiency.

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1. Introduction

The increasing demand of energy promotes the study of new solutions able to replace the use of fossil fuels and, in this scenario, hydrogen is considered one of the most promising energy carriers that could be used to exploit the renewable sources [1–3]. Furthermore, the use of hydrogen is particularly beneficial when fuel cell systems are adopted for the production of electrical power due to the low polluting emission [4–8]. On the other hand, one of the main drawbacks of the hydrogen based technologies is the clean production by using

renewable and environment friendly processes [9–11]; in fact, it is commonly known that the current production comes from natural gas reforming and thus hydrogen cannot be considered neither renewable nor zero emission fuel when a cradle to grave analysis is considered [12–14]. In addition, transportation and storage of hydrogen are also critical issues that play a significant role when evaluating a technology for hydrogen production [15–18].

Recently, many studies are investigating the reaction of metals with water to produce hydrogen and particular attention is devoted to the use of aluminum [19–24]. The present

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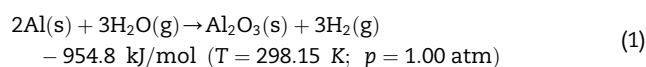
Nomenclature			
Al(s)	Aluminum in state of solid	P_{el}	Electric power output
Al ₂ O ₃ (s)	Aluminum oxide in state of solid	P_{H_2}	Hydrogen chemical power
BSFC	Brake Specific Fuel Consumption	P_{loss}	System total power loss
C.C.	Combustion Chamber	P_{out}	Total power output of the system
E_c	Energy production cost	Pre-H.	Water pre-Heater
G	Electric generator	$P_{th,C.C.,loss}$	Thermal power loss through the C.C. walls
H ₂ (g)	Hydrogen in state of gas	$P_{th,S.G.,loss}$	Thermal power loss through the S.G. walls
H ₂ O(l)	Water in state of liquid	$P_{th,rea}$	Theoretical thermal power released by the reaction
H ₂ O(g)	Water in state of gas	P_{turb}	Turbine input power
H ₂ O(g/l)	Water in state of wet vapor	S.D.	Steam Drum
LHV _{Al}	Aluminum Lower Heating Value	S.G.	Steam Generator
LHV _{H₂}	Hydrogen Lower Heating Value	S.T.	Steam Turbine
LME _{Al}	Primary Aluminum price based on London Metal Exchange value	T_{CC}	Combustion chamber temperature
l.p.S.D.	Low pressure Steam Drum	$T_{S.G.,max}$	Maximum Steam Generator temperature
\dot{m}_{Al}	Production rate of aluminum particle	x_s	Steam quality
\dot{m}_{H_2}	Hydrogen mass flow rate	λ	Oxidizer/fuel ratio
\dot{m}_{H_2O}	Water mass flow rate into the combustion chamber	η_c	Combustion efficiency
p_{cc}	Combustion chamber pressure	η_{el}	Electric energy conversion efficiency
$P_{Al,unburned}$	Power loss due to unburned aluminum	η_{th}	Thermal efficiency of the combustion chamber
		η_{tot}	Global efficiency of the system
		η_{turb}	Total turbine and electric generator efficiency

paper is focused on the development of a new hydrogen and power production system based on the aluminum combustion with water described in Ref. [25]. The system can be used for local hydrogen production by exploiting the aluminum water steam reaction and thus, instead of transporting and storing of H₂, aluminum is transported and accumulated. The system is particularly advantageous when a renewable energy source is available, i.e. wind, solar or hydro, but it is located far from a possible utilization site, such as an urban or industrial area. In this case, aluminum is produced using the renewable electric energy and transported to the utilization site and converted back to hydrogen and power by means of the proposed system. The system by-product, i.e. the alumina, can be then recycled back where the renewable energy source is located and retransformed into aluminum in a closed cycle.

Four different layouts of the proposed co-generation system are investigated and compared in terms of energy conversion efficiency, brake specific fuel consumption and electrical power output by means of a lumped and distributed parameter numerical simulation.

2. Description of the analyzed power plant configurations

The co-generation system presented in this paper is more extensively described in Ref. [25] and the turbine operation and the combustion chamber architecture are studied in Refs. [26] and [27]. The system is potentially able to produce continuously hydrogen, high temperature steam, heat and work at the turbine shaft, by the exploitation of the highly exothermal oxidation of aluminum with water steam (1).



In the standard use of aluminum for industrial components, the metal is passivated by an aluminum oxide layer. The proposed system can remove the aluminum oxide layer from the aluminum surface and produce aluminum particles with an average dimension lower than 0.05 mm [28–32].

In this analysis the differences between four layouts of the co-generation system are investigated. The layouts exploit the thermal power of the gaseous combustion products to heat up an amount of water used in a super-heated steam turbine cycle in a way similar to a traditional steam generator. The water enters the combustion chamber upstream the aluminum particles duct with a flow rate slightly exceeding the stoichiometric amount. The heat released during the combustion process is used to vaporize the working cycle water flowing through the wall tubes which cover the inner and outer walls of the combustion chamber (C.C.). These tubes are the first part of the evaporator of the steam generator (S.G.) located downstream of the combustor.

In order to define system operating conditions, the extra water amount is evaluated in terms of the following parameter:

$$\lambda = \frac{\dot{m}_{H_2O}}{\left(\frac{\dot{m}_{Al}}{\dot{m}_{Al}}\right)_{stoic}} \quad (2)$$

This parameter relates the total amount of water flowing through the combustion chamber to the stoichiometric value for the Al–H₂O reaction; therefore, when λ is larger than one, the exceeding water can be vaporized. If the system operates with λ lower than one, unburned aluminum is remaining due to the lack of water and the total energy conversion efficiency is decreasing.

In Figs. 1–4, the continuous lines represent the flow through the combustion chamber, the dashed lines denote the

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