INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 7209–7217

Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

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

Stefano Mercati, Massimo Milani, Luca Montorsi*, Fabrizio Paltrinieri

DISMI, University of Modena and Reggio Emilia, Via Amendola 2, Pad. Morselli, 42122 Reggio Emilia, Italy

ARTICLE INFO

Article history:
Received 25 January 2013
Received in revised form
3 April 2013
Accepted 5 April 2013
Available online 9 May 2013

Keywords:
Hydrogen production
Aluminum combustion
Energy conversion
Plant optimization

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.

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

* *Corresponding author*. Tel.: +39 0522 522 603; fax: +39 0522 522 609.
E-mail address: luca.montorsi@unimore.it (L. Montorsi).
0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.04.043

Nomenclature

Al(s)	Aluminum in state of solid
$Al_2O_3(s)$	Aluminum oxide in state of solid
BSFC	Brake Specific Fuel Consumption
C.C.	Combustion Chamber
E_c	Energy production cost
G	Electric generator
$H_2(g)$	Hydrogen in state of gas
$H_2O(l)$	Water in state of liquid
$H_2O(g)$	Water in state of gas
$H_2O(g/l)$	Water in state of wet vapor
LHV_{Al}	Aluminum Lower Heating Value
LHV_{H_2}	Hydrogen Lower Heating Value
LME_{Al}	Primary Aluminum price based on London Metal Exchange value
l.p.S.D.	Low pressure Steam Drum
$\dot{m}_{Al}$	Production rate of aluminum particle
$\dot{m}_{H_2}$	Hydrogen mass flow rate
$\dot{m}_{H_2O}$	Water mass flow rate into the combustion chamber
p_{cc}	Combustion chamber pressure
$P_{Al,unburned}$	Power loss due to unburned aluminum
P_{el}	Electric power output
P_{H_2}	Hydrogen chemical power
P_{loss}	System total power loss
P_{out}	Total power output of the system
Pre-H.	Water pre-Heater
$P_{th,C.C.,loss}$	Thermal power loss through the C.C. walls
$P_{th,S.G.,loss}$	Thermal power loss through the S.G. walls
$P_{th,rea}$	Theoretical thermal power released by the reaction
P_{turb}	Turbine input power
S.D.	Steam Drum
S.G.	Steam Generator
S.T.	Steam Turbine
T_{CC}	Combustion chamber temperature
$T_{S.G.max}$	Maximum Steam Generator temperature
x_s	Steam quality
λ	Oxidizer/fuel ratio
η_c	Combustion efficiency
η_{el}	Electric energy conversion efficiency
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 H_2, 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, break 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).

$$2Al(s) + 3H_2O(g) \rightarrow Al_2O_3(s) + 3H_2(g) \\ - 954.8\ \text{kJ/mol}\ (T = 298.15\ K;\ p = 1.00\ \text{atm}) \quad (1)$$

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:

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

This parameter relates the total amount of water flowing through the combustion chamber to the stoichiometric value for the Al–H_2O 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