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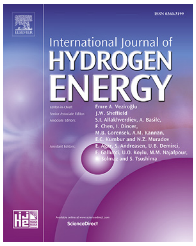

Modelling of aluminum-fuelled power plant with steam-hydrogen enthalpy utilization

M.S. Vlaskin[*], *A.O. Dudoladov*, *O.A. Buryakovskaya*, *G.N. Ambaryan*

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya Str., 13, Build. 2, 125412 Moscow, Russia

ARTICLE INFO

Article history:
Received 19 October 2017
Received in revised form
30 December 2017
Accepted 7 January 2018
Available online xxx

Keywords:
Hydrogen production
Aluminum-water reactor
Power plant
Gas turbine

ABSTRACT

Present paper is devoted to the modelling of aluminum-fuelled power plants which employ an aluminum-water reactor for hydrogen and heat production. We considered two new schemes for power plants with aluminum-water reactors producing high-temperature steam-hydrogen mixture: a power plant with a steam-hydrogen turbine, condenser and air-hydrogen fuel cell and a power plant with a steam-hydrogen turbine, combustion chamber and steam-gas turbine. Parameters of the aluminum-water reactor described in the paper correspond to those of the recently developed and tested aluminum-water reactor: pressure – 15 MPa, temperature – 600 K, steam to hydrogen mass ratio – 40. It was shown that the electrical efficiency can be increased from 12% to 25–30% for the power plant with an air-hydrogen fuel cell and to 18–25% for that with a combustion chamber and steam-gas turbine. The total efficiency of such power plants can reach 80%. Moreover, the efficiency of aluminum-fuelled power plants can be further increased by heat regeneration or heat transfer to the secondary circuit. The proposed calculation method provides high accuracy and can be used to predict the performance of power plants with aluminum-water reactors under different operation conditions. In general, the proposed method can be used to simulate utilization of the enthalpy of high-temperature steam-hydrogen mixture from various sources.

Introduction

Modern energy challenges create demand for new energy carriers with competitive characteristics. In recent years hydrogen has been considered as such. It can be produced from water through electrolysis that means that the potential reserve of hydrogen on the Earth is practically unlimited. Hydrogen is environmentally friendly because its combustion is less polluting than that of fossil fuels, so the use of hydrogen for energy production decreases the charges for eco-activity. However, hydrogen still does not play a significant role in energy sector mainly due to storage and transportation problems, which are still open as decades ago.

There were many attempts to resolve the problem of hydrogen storage and transportation. A mature technology for hydrogen storage is liquid hydrogen storage that provides the highest storage capacity [1]. However, hydrogen exists as a saturated liquid at 1 bar under a cryogenic temperature as low as around 20 K (–253 °C) that restricts the application of this

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[*] *Corresponding author*. Joint Institute for High Temperatures of the Russian Academy of Science, Izhorskaya Str., 13, Build. 2, 125412 Moscow, Russia.

E-mail address: vlaskin@inbox.ru (M.S. Vlaskin).

https://doi.org/10.1016/j.ijhydene.2018.01.023

Please cite this article in press as: Vlaskin MS, et al., Modelling of aluminum-fuelled power plant with steam-hydrogen enthalpy utilization, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.01.023

technology. Another wide-used method of hydrogen storage is compressed hydrogen storage [2]. In this case hydrogen is stored in 20–30 MPa (metallic) gas cylinders which, however, have poor storage capacity (about 1 wt%), much lower than the target values for most hydrogen applications. One of the promising ways for hydrogen storage and transportation is implementation of metal hydrides. At the same time, most of the known compounds have a reversible storage capacity less than 3 wt% [2]. Over the past years liquid organic hydrogen carriers have gained increased attention [3–5]. Different liquid organic hydrogen carriers have from 4 to 7 wt% hydrogen storage capacity [4]. Thus, toluene, naphthalene and benzene react with hydrogen with formation of stable organic hydrides such as methylcyclohexane, decalin and cyclohexane [6,7]. Main limitations for this method of hydrogen storage are related to the amount of energy required to extract hydrogen from the liquid organic hydride and the insufficient stability of the dehydrogenation catalyst [8]. Ammonia as a hydrogen carrier has a capacity of 17.8 wt%, and there are ongoing studies aiming to improve the efficiency of hydrogen-to-ammonia conversion [9]. Other methods for hydrogen storage and transportation include also hydrogen storage in sorbents [10], clathrate hydrates [11] etc. Comprehensive reviews of different approaches were published as well [12,13].

In recent years the interest in non-organic energy carriers has increased [14]. A number of researchers find aluminum an advantageous non-organic energy carrier representing both the source of energy (in case of its combustion) and the source of hydrogen (in case of its hydrolysis). Aluminum has high potential for its integration into energy economy of the future because of the high content of aluminum in the Earth's crust, its safety and moderate cost of aluminum storage and transportation [15], as well as possible regeneration of this energy carrier.

One of the promising ways to convert aluminum chemical energy into useful forms is aluminum oxidation in liquid water or water steam with heat and hydrogen production [14]. When aluminum reacts with water, 15–16 MJ of heat, about 1.9 kg of aluminum oxide and 0.111 kg of H_2 are produced per a kg of aluminum. It corresponds to 11.1 wt% of hydrogen storage capacity. Oxidation products (aluminum oxide or hydroxide) can be returned into the cycle of aluminum production or used for the production of adsorbents, catalysts, insulators, high-purity aluminas and other [16–19].

Aluminum oxidation in water under standard conditions is impossible due to formation of an oxide film on its surface. The development of methods for aluminum surface activation or oxide film destruction for fast and complete aluminum oxidation is an important task [14]. A number of methods of aluminum activation have already been proposed. These methods include preparation of highly reactive aluminum powder alloyed with gallams of various compositions including Ga, In, Sn, Zn and other additives [20,21]. Enhanced aluminum oxidation in water is observed after aluminum co-milling with graphite [22] and silicon [23]. The surface of aluminum particles is activated by milling with different metal oxides such as Al_2O_3, TiO_2, Co_3O_4, Cr_2O_3, Fe_2O_3, Mn_2O_3, NiO, CuO, ZnO, MoO_3, Bi_2O_3 and other [24–26]. Milling with salts was also proposed as a perspective way of aluminum activation [27–29]. New aluminum surfaces created by milling are covered with salt preventing aluminum oxidation during its storage, these surfaces become accessible as the salt dissolves in aqueous medium. Aluminum oxidation can be accelerated in alkaline aqueous solutions [30]. There are also incalculable quantity of methods which assume the use of additional chemicals to realize fast and complete aluminum oxidation in aqueous media.

A recently developed method of aluminum micron powder oxidation in high-temperature steam [31–33] allowed applying pure (without alkali and any other chemical activators) water as oxidant. Kinetics of aluminum micron powders oxidation in high-temperature boiling water was studied in Refs. [34,35]. It was established that commercial aluminum powders with average particle sizes from 4 to 70 μm were intensively oxidized by water steam under about 300 °C and 10 MPa within a special reactor; the reaction time was several tens of seconds.

Further development of power plants with ‘ aluminum-water’reactors as high-pressure steam-hydrogen generators was based on the results of kinetic experiments and a number of designing investigations. Calculations for such systems were described in Ref. [32]. That study was devoted to thermodynamic processes during continuous reactor operation. In that work the reactor's thermo- and gas-dynamic parameters estimation and optimization were carried out, and the optimum values (temperature, pressure, volume etc.) providing the maximum thermodynamic effectiveness were determined.

Based on the results of [31–35] and some other designing investigations an experimental co-generation aluminum-fuelled power plant was developed [36]. It consumes aluminum micron powder as primary fuel and pure water as primary oxidant. Hydrogen, which is produced within the aluminum-water reactor, is used as secondary fuel for electrical energy generation via an air-hydrogen fuel cell battery. The nominal hydrogen generation rate of the plant is 10 m^3/h. The abovementioned power plant outputs useful electrical energy and heat, and it can also produce hydrogen as the end product. From 1 kg of aluminum the power plant produces 1 kWh of electrical energy and 5/7 kWh of heat. The plant's electrical and total efficiencies (relative to the chemical energy of aluminum) are 12% and 72% respectively.

Low electrical efficiency of the created aluminum-fueled power plant is accounted for by the fact that only chemical energy of hydrogen is converted into useful electrical energy while the heat of aluminum-water reaction is not used. It ought to be noted that the enthalpy of aluminum-water reaction per a kg of Al is about 15–16 MJ and it is comparable with the chemical energy of 0.111 g of hydrogen produced from a kg of Al. So it is profitable to convert the enthalpy of aluminum-water reaction into useful electrical energy as well.

One of the possible ways to convert the enthalpy of aluminum-water reaction into useful electrical energy is to install a gas turbine downstream of the aluminum-water reactor and upstream of a fuel cell. In this case steam-hydrogen mixture generated in the aluminum-water reactor expands in the steam-hydrogen turbine, then water is condensed in a condenser and then hydrogen is consumed by the air-hydrogen fuel cell battery (Fig. 1). Another way (without a fuel cell) is the combustion of hydrogen within a

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