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Efficiency analysis of a novel electricity and heat co-generation system in the basis of aluminum–water reaction

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ABSTRACT

With high calorific value and the environmental friendly features, hydrogen has been attached much importance. Aluminum–water reactions at medium–high temperature perform well in hydrogen generation as well as heat utilization. Active researches of the aluminum–water reactions in recent years can be attributed to the increasing interest of hydrogen generation and energy conversion.

In the basis of aluminum–water reactions, the concept of a novel electricity and heat co-generation system was proposed here and it was primarily composed of a reactor, one or two turbines and generators, heat exchanger for heat user, a fuel cell and a pump. Two layouts were designed and analyzed: the one turbine layout (OTL) and the two turbine layout (TTL).

The effects of key parameters, such as the steam temperature and pressure at turbine inlet, the heat user temperature and fuel cell conversion efficiency were investigated. The co-generation system could generate heat and electricity of about 22.2 MJ/kg (Al) in the OTL design. The system utilization efficiency, the ratio of the output was approximate 70% and the electricity generation efficiency could reach up to 41.52% (OTL) and 49.25% (TTL) in the two cases respectively. The OTL presented a higher heat user utilization efficiency than TTL, because of the higher turbine outlet parameters. The TTL layout with the integration of fuel cell and heat user enhanced electricity output by 45.06% in comparison with the OTL layout. The steam temperature at turbine inlet showed considerable impacts on the system utilization efficiency at the TTL case. Enhancing fuel cell conversion efficiency benefited the system and fuel cell utilization efficiencies, especially at the TTL case.

Introduction

Aluminum is the most abundant crustal metal on the earth and it can be completely recycled in theory. Because aluminum and its alloys present a number of valuable thermal, electrical and mechanical properties, they are widely used in various fields. Noticing its high energy density of 29 MJ/kg, aluminum is considered as one of energy carriers.

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Nomenclature

Q	heating value of aluminum combustion in O_2 atmosphere, kj/kg
Q′	heating value of aluminum combustion in H_2O atmosphere, kj/kg
Q″	hydrogen lower heating value, kj/kg
T	temperature, K
P	pressure, MPa
H	enthalpy, kj/kg
λ	steam/hydrogen mass ratio
E	output energy, electricity or heat, kj/kg
eff	equipment conversion efficiency, %
η	utilization efficiency, %
Subscript	
r	reactor
hu	heat user
t	turbine
s	steam
h	hydrogen
i	inlet
o	outlet
fc	fuel cell
e	electricity
OTL	the first system layout with one turbine
TTL	the second system layout with two turbines

Aluminum batteries is one of energy utilization ways [1,2]. Hydrogen generation from aluminum–water reaction is considered as one kind of environmentally friendly fuels. Since the early 1950s, aluminum combustion has been studied on due to its utilization in the propulsion [3,4]. In recent years, an increasing concern of aluminum utilization as an energy storage or conversion material has appeared [5–7].

Metallic fuels such as boron and magnesium also have high energy densities. But why we didn't choose them rather than aluminum? In the electricity and heat co-generation system described below, aluminum was heated over its melting point and reached to a certain high temperature and then reacted with heated water. Aluminum has got a proper melting point at 660 °C, and a high boiling point at 2327 °C. Boron has got a much higher melting point at 2076 °C than aluminum, so it is really tough to make it molten. As for magnesium, it has an equivalent melting point as aluminum, but its boiling point is much lower than aluminum, so it can't avoid boiling while reacting.

Besides the researches of aluminum combustion in an oxygen, or air or carbon dioxide or water atmosphere [8–12], hydrogen generation from aluminum has been concerned. Though approximate 95% of hydrogen is generated by natural gas reforming and coal gasification at present [13], they cannot act as long-term strategies because the raw materials are all based on fossil fuels. Hydrogen generation from aluminum hydrolysis will be a good option if aluminum is produced by using renewable energy. Furthermore, the products of aluminum hydrolysis are aluminum hydroxide and alumina, and both of them yield low environmental impacts and can be recycled or used as industry materials. It is well recognized that a passive oxide film which covers on the aluminum particle surface generally hinders aluminum hydrolysis. Removing the passive oxide film and keeping aluminum in an activated state are essential to yield hydrogen. The methods including mechanical polishing or cutting, adding alkaline catalysts or oxides or carbon materials, doping some metal elements to form aluminum alloys and elevating temperatures [14–16] have been and are being researched on.

Aluminum–water reaction releases abundant heat and the energy stored in the hydrogen generated from aluminum is only about 50%. Some concepts of aluminum-fueled systems were proposed and investigated to utilize both hydrogen and the released heat, which led to a higher energy efficiency. The energy conversion efficiency of an Al–H_2O power system was estimated when adopting a superheated steam cycle or a combine heat and power cycle. In both cases, the efficiency ranged between 0.62 and 0.85 respectively when employing the hydrogen in a fuel cell [17]. Valskin et al. have done some experiments on a power plant using aluminum powder (with an average particle size of 70 μm) and water as fuel and oxidant respectively [18]. From 1 kg of aluminum the experimental plant produced 1 kWh of electricity and 5–7 kWh of heat with electricity efficiency of 12% and total efficiency of 72%. Mercati and his colleagues investigated the preliminary design of a superheated steam and hydrogen co-generation system in the basis of the combustion of aluminum particles with water. Total energy conversion efficiency was varied depending on pressure and temperature of combustion chamber, water/aluminum ratio and turbine rotational speed [19]. The electric efficiency could reach up to 8% and total conversion efficiency 78%, which resulted in a lower energy cost of 5.13 USD/kWh [20]. If scrap aluminum was used to react with water, the energy cost would be reduced significantly [7,21].

The above mentioned systems always used fine aluminum particles with a size of 70–20 μm as fuel and a grinding tool was necessary to mill aluminum bars. In this paper, the concept of a novel electricity and heat co-generation system was proposed in the basis of Al–H_2O reaction. Hydrogen generation and superheated steam production took place in a same device in which aluminum was liquid and temperature was some higher than aluminum melting point during the operation. The specialties of the system included Al–H_2O reaction under high temperature, fast reaction rate and hydrogen generation, aluminum block instead of powder, omitting hydrogen compression, and reaction heat utilization. The efficiencies of the co-generation system and steam turbine were analyzed and the effects of key parameters were investigated.

Concept description of the co-generation system

Fig. 1 presented two layouts of the cogeneration system: the one turbine layout (OTL) and the two turbine layout (TTL). Both of the two layouts were primarily composed of a reactor, one or two turbines and generators, a heat exchanger for heat user, a fuel cell and a pump. A big block or some small blocks of aluminum or aluminum alloy was placed in the reactor. Before the cogeneration system started aluminum was heated