Materials Science for Energy Technologies 3 (2020) 250–254

Contents lists available at ScienceDirect

Materials Science for Energy Technologies

journal homepage: www.keaipublishing.com/en/journals/materials-science-for-energy-technologies

Valorization and sequestration of hydrogen gas from biomass combustion in solid waste incineration NaOH oxides of carbon entrapment model (SWI-NaOH-OCE Model)

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ARTICLE INFO

Article history:
Received 3 November 2019
Revised 22 November 2019
Accepted 23 November 2019
Available online 11 December 2019

Keywords:
Biomass valorization
Hydrogen gas sequestration
Oxides of carbon entrapment
Geomaterials
Biogas
Hydrogen cell battery
Hydrogen cell fuel

ABSTRACT

The valorization of biomass-based solid wastes for both geotechnical engineering purposes and energy needs has been reviewed to achieve eco-friendly, eco-efficient and sustainable engineering and reengineering of civil engineering materials and structures. The objective of this work was to review the procedure developed by SWI-NaOH-OCE Model for the valorization of biomass through controlled direct combustion and the sequestration of hydrogen gas for energy needs. The incineration model gave a lead to the sequestration of emissions released during the direct combustion of biomass and the subsequent entrapment of oxides of carbon and the eventual release of abundant hydrogen gas in the entrapment jar. The generation of geomaterials ash for the purpose of soil stabilization, concrete and asphalt modification has encouraged greenhouse emissions but eventually the technology that has been put in place has made it possible to manage and extract these emissions for energy needs. The contribution from researchers has shown that hydrogen sequestration from other sources requires high amount of energy because of the lower energy states of the compounds undergoing thermal decomposition. But this work has presented a more efficient approach to release hydrogen gas, which can easily be extracted and stored to meet the energy needs of the future as fuel cell batteries to power vehicles, mobile devices, robotic systems, etc. More so, the development of MXene as an exfoliated two-dimensional nanosheets with permeability and filtration selectivity properties, which are connected to its chemical composition and structure used in hydrogen gas extraction and separation from its molecular combination, has presented an efficient procedure for the production and management of hydrogen gas for energy purposes.

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Peer review under responsibility of KeAi Communications Co., Ltd.

https://doi.org/10.1016/j.mset.2019.11.003

Contents

1. Introduction

Solid waste handling and management around the world and especially in the third world countries have contributed to the alarming amounts of carbon oxides emission and on the threat of global warming. On the other hand, these waste materials are intentionally and technically valorized through the process of direct combustion in an attempt to generate geomaterials in the form of ash [1–5]. Unfortunately, it has been observed that there are shocking threats to environmental safety due to the release of oxides of carbon during incineration. These ash geomaterials have been utilized by geotechnical engineering experts in the treatment, stabilization and modification of soil for various engineering purposes due to their amorphous and pozzolanic properties [6]. They exhibit high cementing properties thereby serve as supplementary cementitious materials in a binding procedure. However, the process by which these materials are derived poses a threat to the environment due to carbon emission. A model was developed by Onyelowe et al. [7], which is called Solid Waste Incineration NaOH Oxides of Carbon Entrapment Model (SWI-NaOH-OCE Model). In this model as present in Fig. 1, the affinity between sodium hydroxide (NaOH) and oxides of carbon is utilized to trap the CO and CO_2 emitted during the combustion of solid waste biomass in a jar. The model is such that ensures that CO and CO_2 released during solid waste combustion is entrapped by caustic soda solution (prepared NaOH, 40% w/v). 100% of the CO and CO_2 released is trapped by the caustic soda solution because of the strong affinity caustic soda has with oxides of carbon. This entrapment produces sodium bicarbonate (baking soda, $NaHCO_3$), sodium carbonate (soda ash, Na_2CO_3) and hydrogen gas (H_2) presented in Eqs. (1) and (2);

$$NaOH + CO_2 >>>>>>>>>>>> NaHCO_3 \quad (1)$$

$$2NaOH + CO >>>>>>>>>>>>>> Na_2CO_3 + H_2 \uparrow \quad (2)$$

This combustion process is done in a controlled incineration mechanism, which ensures that the oxides of carbon released don't escape and find their way into the atmosphere.

Particular interest is placed on the product of the sodium hydroxide and oxides of carbon affinity, which is the biogas or biofuel (hydrogen gas) released in Eq. (2). Underlying the use of hydrogen as a fuel is the fundamental question, where does it exist and how do we get it? With its plenteous supply in the universe, hydrogen (gas or liquid) does not exist free of other elements because it is constantly bound into molecular compounds. The process of obtaining hydrogen gas is one of removing it from these other molecules that must have been in affinity with this fuel gas. This is a form of hydrogen capture or sequestration. This present research has a core objective of reviewing capturing the abundance of hydrogen released in the SWI-NaOH-OCE Model presented in Fig. 1. The free abundance hydrogen from the model aforementioned and illustrated exist in a mixture of soda ash, baking soda and possibly other unidentified gaseous compounds as shown in the outlet of the model. This model is the result of direct

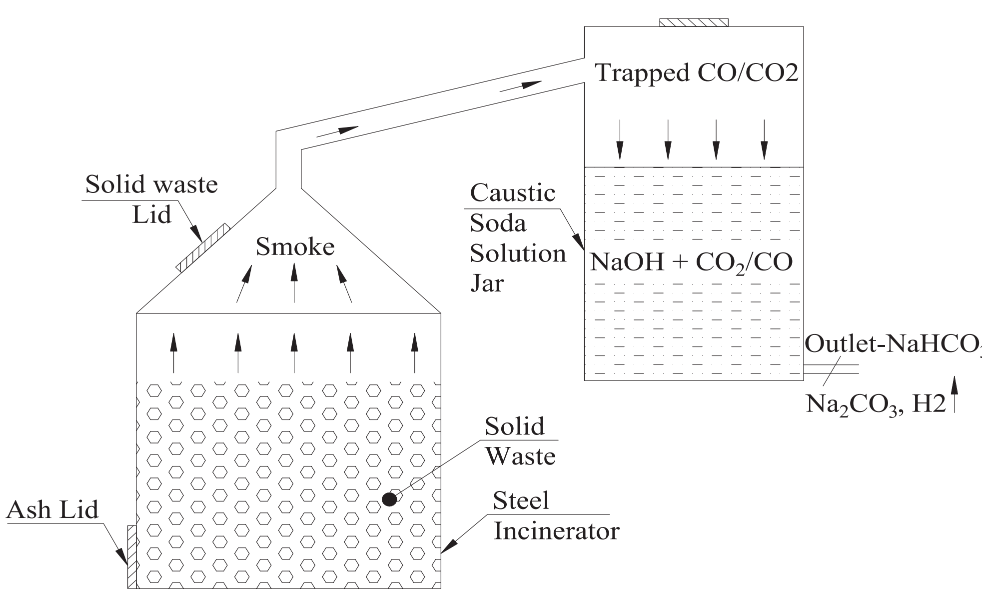


Fig. 1. SWI-NaOH-OCEM for Solid Waste Combustion and CO/CO_2 Entrapment [7].

combustion of biomass materials as solid waste to obtain ash, which is utilized as a geomaterial for foundation construction purposes [1–4,7]. This sequestration or hydrogen capture procedure is possible under low energy requirements because the outlet products within which the abundance hydrogen exists are of higher energy state compared to hydrogen. So, it takes less energy to extract or capture the hydrogen gas for use as an energy source.

2. Review of relevant literature

In 2001, the College of the Desert researched on hydrogen use and proceeded with an attempt to manufacture hydrogen centered around the extraction of hydrogen from water in what is called electrolysis [8]. He established that hydrogen can be extracted under less pollution and can at the same time be renewable but that it required the input of large amount of electrical energy. This paper went on to state the total environmental impact of manufacturing hydrogen through electrolysis hugely depends on the source power impact on the entire set up. It also stated the total amount of carbon dioxide emission of electrolysis and reforming of various fuels as one way to assess the comparative environmental impact. Note also here that the model illustrated above has been confirmed a wonderful procedure of carbon capturing through sodium hydroxide affinity with its oxides.

Castro et al. [9] worked on the synthesis of hydrogen gas by thermal decomposition of methane gas with carbon sequestration in 2008 [9]. In this method to manufacture hydrogen gas, it was shown that thermodynamic energy was useful to predict the different species formation when they are found in complex compounds under a reactor of plasma. This experimental system adopted very complex reactions in a reactor by introducing fine silicon powder an agent of carbon fixation to enhance the thermal decomposition process, which is of a low energy state that requires higher amount of energy in the form of heat to achieve sequestration of carbon and manufacture of hydrogen gas. Over a number of 12 runs of thermal decomposition procedure was used to separate the methane gas in a plasma torch model Plazjet 105/15 using two power levels and three different methane gas flow rates of 300, 500 and 750 ml/min. Though this process was proved to be an effective process but the energy consumption to raise the low state of energy of the compounds in the reactor makes it expensive.

Ogden had in 2002 worked on modeling infrastructure for a fossil hydrogen energy system with CO_2 sequestration [10]. Ogden made a sincere attempt in his modelled set for the production of hydrogen gas from fossil fuels with CO_2 capture and sequestration but left a loophole where the two emissions are transported through two running pipelines with CO_2 discharged to disposal sites. Incorporating a model that utilizes the affinity between CO_2 and sodium hydrogen would have left Ogden's model as a flawless and efficient design that takes care of all emissions not letting any hazards into the environment.

In 2012 with support from the U. S. Department of Energy, Howard took up the challenge to work on the economics of CO_2 separation and capture. This research established that carbon management and sequestration offer opportunities for reducing greenhouse gas emissions that can support the present-day efforts and plans to improve energy efficiency [5]. It further stated that this would eventually increase the utilization of non-fossil energy sources. He presented an overview of CO_2 separation and capture technology and moving forward was a detailed cost associated with current technology for CO_2 separation and capture. Though this was followed with an analysis of how to lower costs in the future, which was timely, the procedure is lacking in what could be achieved to boost today's energy needs through further conversion of CO_2 to yield hydrogen gas.

According to Neha and Vineet [11], overdependence on fossil fuels is directly linked air pollution and global warming, which are two major environmental hazards faced by humanity today. In their work, "fundamentals and use of hydrogen as a fuel", it is established that hydrogen atom is chemically very reactive, which is why it is not naturally found chemically free. Also, it should be noted from the result of their research that very high temperatures are needed to dissociate molecular hydrogen to atomic hydrogen in a hydrogen sequestration process. This research expressed the challenges involved in storing either liquid hydrogen in cryogenic tank or gaseous hydrogen in a pressurized tank as the amount of energy that can be stored in an available space due to its low density. Further, Neha and Vineet stated the appeals societally and technically, as a potential solution to make abundant supply of energy available with minimal environmental impact and at very low economy. They have stated that hydrogen has the potential to be the attractive energy vector for future fuel needs, which can be produced from various sources, which includes biomass, wastes, coal and reactors.

Moura et al. had in 2015 also worked on an education program to educate engineers on the fundamentals of modeling, control, and design of batteries, fuel cells and hydrogen storage devices [12]. This came up in a collaborative effort by three universities in Michigan U. S. to point the energy needs of the future to hydrogen capture and its utilization in fuel cells, batteries, cell vehicles and hydrogen infrastructures. The transformation of automotive industries' workforce is on the way as hydrogen stands in to boost vehicle electrification systems. The problem has been to establishment of a well-defined path for CO_2 sequestration and conversion to usable energy to also boost the biogas needs for the future.

Offer et al. in 2010 researched on the comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system, where the performance and efficiency of battery electric vehicles and hydrogen fuel cell batteries were studied [13]. Offer et al. in the work established that the energy needs for the future should best be anchored on hydrogen fuel because of its sensitivity to hydrogen cost and environmentally friendly process.

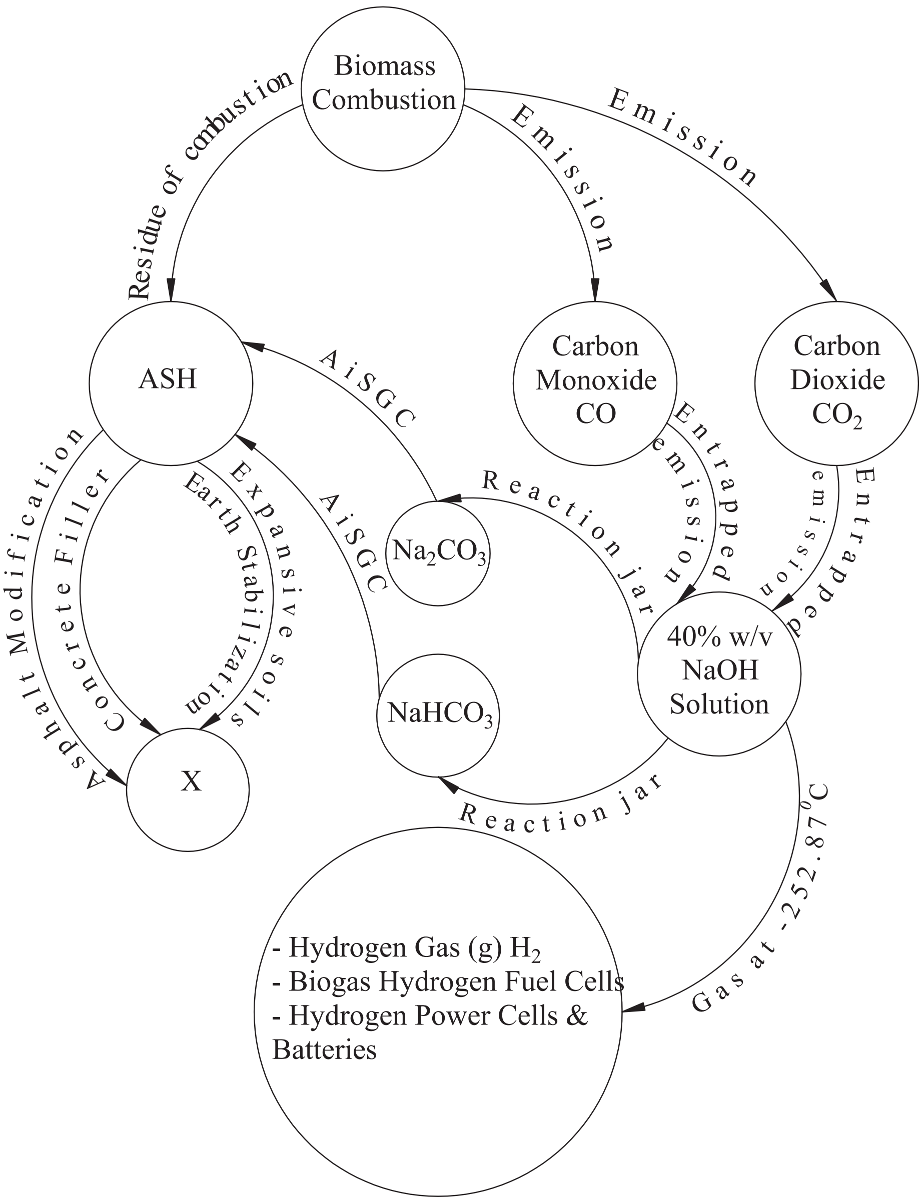
According to Salminen et al. [14], fuel cells achieved through electrolysis are open electrochemical energy conversion and power preservation systems where chemical energy is directly converted to into power by reduction and oxidation occurring at the poles of the electrochemical cell [14]. This process is characterized with CO_2 emissions, which are released and eventually contribute to environmental hazards. Biomass-based solid wastes are being studied as a source for the future energy needs. This will eventually replace overdependence on fossil-based fuel energy, which has killed the planet with greenhouse emissions.

Anahita et al. [15] had work on a combined cycle of gas firing and biomass post-firing which involved the injection of hydrogen gas as a source of bioenergy. This work stated the advantages of hydrogen injection and non-injection on the exergy impact.

Reddy et al. [16], Sajid et al. [17] and Aslam et al. [18] also presented the photocatalytic production of hydrogen gas by utilizing the plenty active sites and surface areas present in nanoparticles of biomass materials.

3. Biomass valorization by combustion and sequestration of hydrogen gas

In an effort to manage biomass-based solid waste and at the same time derive geomaterials utilized by the geotechnical engineer in the stabilization and improvement of soft soil properties for construction purposes, biomass-based solid waste materials are converted to ash by direct combustion. Through this procedure,



**AiSGC: Additives in the synthesis of geopolymer cement*

X: Ecofriendly, Ecoefficient & Sustainable Infrastructure Foundations

Fig. 2. Biomass valorization, carbon sequestration and hydrogen gas separation and capture cycle.

ash is generated and utilized in various engineering works, for instance, because of its high pozzolanic property due to the presence of aluminosilicates, ash is used as a supplementary cementing material in soils stabilization, asphalt and concrete production. This whole procedure of utilizing ash to replace the conventional cement serves as an effort to reduce greenhouse emission and global warming effects due to the release of CO_2 from the use of ordinary cement in civil engineering works. Having achieve zero CO_2 emission by replacing cement with ash, the whole process is now faced with the CO_2 released during the direct combustion of biomass-based solid wastes. In the Solid Waste Incineration Sodium Hydroxide Oxides of Carbon Entrapment Model developed by Onyelowe et al. [7] and illustrated in Fig. 1, the direct combustion is done in a controlled combustion chamber, which allows all the released oxides of carbon to be entrapped through the strong affinity with sodium hydroxide to leave as residue in the entrapment jar; soda ash, baking soda and abundant emission of hydrogen gas. This valorization process is illustrated in Fig. 2. The sequestration of hydrogen gas released from the SWI-NaOH-OCE Model becomes a complex one due to the fact that hydrogen exist in molecular compounds and its separation and storage is equally an arduous and cumbersome task [1–4]. Through thermal decomposition, efficient residue cleanup for the $NaHCO_3$ and Na_2CO_3, hydrogen is separated and extracted for storage under pressure as gas or under extreme temperatures as liquid hydrogen in cryogenic storage systems. Hydrogen released from the SWI model can be of immense use in today's energy world in fuel cell batteries. Finally, according to Ding et al. [19], an exceptionally efficient gas with separation properties in a nanomaterial has been uncovered known as MXene that could be incorporated into the membranes used to separate and purify hydrogen. The uncovering of the MXene shows that *"the nanomaterial's two-dimensional struc-*

ture enables it to selectively reject large gas molecules, while letting hydrogen slip between the layers" [19,20]. In this research led by Ding, PhD, it was shown how exfoliated MXene of two-dimensional nanosheets can be utilized as building structural blocks construct laminated membranes for the separation and extraction of hydrogen gas. MXene's permeability and filtration selectivity are connected to its chemical composition and structure and these properties give it the advantage over materials presently being used and developed for gas extraction and separation.

4. Conclusion

The valorization of biomass-based wastes to derive ash as a geomaterial through the direct and controlled combustion and the sequestration of the oxides of carbon and hydrogen gas released in the entire procedure have been reviewed. The end products of the incineration model have shown that hydrogen is in abundant supply through the combustion of solid wastes and can be extracted, separated and stored for use to meet current energy needs. The development of the model to an industrial scale would enhance the management of municipal and biomass-based solid wastes while the generation of ash materials in the process serves the geoenvironmental and construction needs of the geotechnical engineer. More so, the development of MXene as an exfoliated two-dimensional nanosheets with permeability and filtration selectivity properties is also an important part of this review. These are connected to its chemical composition and structure used in hydrogen gas extraction and separation from its molecular combination. More so, it has presented an efficient procedure for the production and management of hydrogen gas for energy purposes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Vietnam Ministry of Education and Training for funding this research, based on Decision No. 5652/QD-BGDDT on December 28, 2018 with Grant No. MOET /2019 and with project number B2019-MDA-08.

Acknowledgement

The authors wish to thank the lead investigator for his ingenuity and the leading role played during the cause of this review.

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