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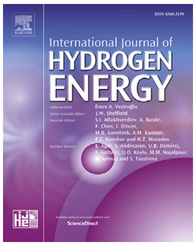

Clean fuel options with hydrogen for sea transportation: A life cycle approach

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ABSTRACT

In this study, two potential fuels, namely hydrogen and ammonia, are alternatively proposed to replace heavy fuel oils in the engines of sea transportation vehicles. A comparative life cycle assessments of different types of sea transportation vehicles are performed to investigate the impacts of fuel switching on the environment. The entire transport life cycle is considered in the life cycle analyses consisting of production of freight ship and tanker; operation of freight ship and tanker; construction and land use of port; operation, maintenance and disposal of port; production and transportation of these clean fuels. Various environmental impact categories, such as global warming, marine sediment ecotoxicity, marine aquatic ecotoxicity, acidification and ozone layer depletion are selected in order to examine the diverse effects of switching to clean fuels in maritime transportation. As a carbon-free fuel for marine vehicle engines, ammonia and hydrogen, yield considerably lower global warming impact during the operation. Furthermore, numerous production methods of alternative fuels are evaluated to comparatively show environmentally benign options. The results of this study demonstrate that if ammonia is even partially utilized in the engines of ocean tankers as dual fuel (with heavy fuel oils), overall life cycle greenhouse gas emissions per tonne-kilometer can be decreased about 27% whereas it can be decreased by about 40% when hydrogen is used as dual fuel.

Introduction

Sea transportation constitutes a large portion of total world transportation. It is principally used for the transportation of goods, liquid fuels, all type of products and humans. Ocean tankers, freight ships and barge tankers require massive amount of energy for operation which is frequently supplied by diesel or residual fuel oils. However, by increasing global warming effect, alternative fuels are considered to replace conventional hydrocarbon fuels. Hydrogen (H_2) and hydrogen carriers are considered as alternative fuel for power generation especially in transportation sector such as maritime. Hydrogen generates more energy per mass in comparison to

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conventional tanker/freight ship fuel which is mostly heavy fuel oil or diesel. The usage of hydrogen in the maritime applications eventually depends on the capability of producing clean, low-cost energy.

Hydrogen carriers include ammonia (NH_3) synthesized from nitrogen and hydrogen that can be used for direct combustion. Ammonia becomes an important hydrogen carrier that does not contain any carbon atoms and has a high hydrogen ratio. Therefore, it is evaluated as a power-generating fuel. It is a molecule which composes of three atoms of hydrogen and one atom of nitrogen. The capability to convert a liquid at adequate pressure permits ammonia to store more hydrogen per unit volume than compressed hydrogen/cryogenic liquid hydrogen. Besides having significant advantages in storing and transporting hydrogen, ammonia may also be burned directly in diesel engines after proper modifications. Ammonia can be easily transferred through pipelines, railway, and ships by delivering to consumption area where it may be utilized as a source of hydrogen, chemical substance, and fertilizer for agriculture, fuel for transportation such as maritime applications. Being a sustainable energy carrier that can be generated from any primary energy source, hydrogen can subsidize to a broadening of vehicle fuel resources and may offer the long term option of being generated from renewable resources. Since ammonia produces mainly water and nitrogen during combustion, replacing a part of conventional fuel with ammonia will have a large effect in reducing carbon dioxide emissions [1]. Ammonia (NH_3) is colorless, pungent gas composed of nitrogen and hydrogen. It is the simplest stable compound of these elements and serves as a feed material for the production of many commercially important nitrogen compounds. The major use of ammonia is as a fertilizer. It is most commonly applied directly to the soil from tanks containing the liquefied gas. Since the improvement potentials of renewable technologies are most likely greater than fossil fuels, it is significant to implement renewable- based alternative fuel production options from environmental point of view [2]. The combustion characteristics of ammonia have been extensively researched in the literature [3–12]. Nozari and Karabeyoglu [4] studied the combustion characteristics of NH_3/H_2/air mixtures at elevated pressure and lean conditions which are encountered in practical systems such as gas turbine combustors. Reiter and Kong [5] investigated the ammonia combustion with ammonia vapor which was introduced into the intake manifold and diesel fuel was injected into the cylinder to initiate combustion. Ezzat and Dincer [6] thermodynamically analyzed two vehicular systems for ammonia-driven vehicles. One of the systems consisted of an internal combustion engine for propulsion and the other one consisted of a fuel cell. Both systems included ammonia decomposition and separation unit which produced hydrogen to be supplied to internal combustion engine or fuel cell. The usage of ammonia integrated to fuel cells was also studied by Zhou et al. [7]. They combined a PEM fuel cell power system, ammonia fuel processing unit and a specific heat-exchanger for a stand-alone PEM fuel cell power generation system. Duynslaegher et al. [8] presented the elaboration of an improved ammonia combustion mechanism validated for the flame structure prediction of ammonia, hydrogen, oxygen, argon flames explored at several low pressures and for numerous situations of equivalence ratio and of initial hydrogen content. Li et al. [9] experimentally tested the combustion characteristics and NOx formation in the combustion of H_2 and NH_3 at different air-fuel equivalence ratios. Hydrogen and ammonia can also be utilized in fuel cells which can be integrated to maritime applications [13].

There are a few technical possibilities for emission reduction in the marine transportation which include more efficient ship hulls, energy-saving engines, more efficient propulsion, and use of alternative fuels and clean technologies such as fuel cells, biofuels or others, devices to trap exhaust emissions [14]. Palit et al. [15] reviewed the usage of biodiesel in transportation sector and concluded that CO, total hydrocarbon and particulate matter emissions from compression ignition engines are largely reduced when biodiesel is used instead of petro-diesel as fuel. Shama [16] performed LCA of ships and resulted in that the highest proportion of energy consumption and environmental impacts are expected to result from operation of ship and requires main change.

Bengtsson et al. [17,18] included fossil based-fuels including marine gas oil with different sulfur content ratios, heavy fuel oil, diesel with different production routes and LNG (liquefied natural gas) in the life cycle assessment study. They concluded that the global warming potential of those selected fuels are not much different although some other environmental impact categories can vary. Mosgaard and Kerndrup [19] evaluated the technologies for energy efficient retrofit solutions for the maritime sector. Blanco-Davis and Zhou [20] emphasized the importance of LCA studies in maritime applications for decision makers. Winebrake et al. [21] used a life cycle model called as TEAMS (Total Energy & Emissions Analysis for Marine Systems) which is similar to GREET. They implied that some alternative fuels may require modifications in infrastructure to make them viable for marine applications. Such a feasibility perspective of achieving NO_x reductions through engine controls on existing oceangoing ships was performed by Corbett and Fischbeck [22]. It is also remarkable to note that the operation efficiencies of the transportation vehicles increased in recent decades; for example marine operation efficiency was 28% in 1970s and increased to 32% in 2010 [23]. Most of the CO_2 emissions (96%) in the complete life cycle is originated from operation of the ship whereas dismantling process of the ship constitutes almost 17% of the total CO emissions [24]. Cichowicz et al. [25] applied an energy efficiency based design index of the ships for different variations of hull roughness, ship speed, ship draught, reefer electric power, power increase due to sea state and their combinations. Additionally, the unloading and loading of the ships at maritime container terminals were studied in terms of optimizing the waiting periods to decrease the total emissions [26]. Singh and Pedersen [27] studied possible waste heat recovery options in the maritime vehicles by considering the properties of shipboard waste heat and achievable recovery efficiencies. Laumann Kjaer et al. [28] integrated life cycle cost study into life cycle assessment by implementing a case study for medium range tankers carrying fuels. They resulted in the case study that fuel for operation of the tanker can account for 89% of total CO_2 emissions but it represents only 36% of the

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