Journal of Cleaner Production 113 (2016) 438–449

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Environmental and economical assessment of alternative marine fuels

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A R T I C L E I N F O

Article history:
Received 27 April 2015
Received in revised form
22 November 2015
Accepted 23 November 2015
Available online 17 December 2015

Keywords:
Hydrogen
Liquefied natural gas
Methanol
Ethanol
Marine engines
Alternative marine fuels

A B S T R A C T

Increasing amount of shipboard emissions, and emission regulations entered into force encourage emission reduction technologies to be developed, and new methods to be used. Alternative fuel use as a fuel on marine diesel engines is one of the new methods to reduce shipboard emissions. Methanol and ethanol can be used as a liquid fuel or liquefied natural gas and hydrogen can be used as a gaseous fuel on ships. Aim of this study is to make scientific comparison of alternative fuels which can be used at ships. The environmental and economical performance of methanol, ethanol, liquefied natural gas, and hydrogen were compared. Comparison was made by eleven comparison criterions from different aspects. The most suitable alternative fuel which can be used on ships is determined by defining evaluation scale points for each comparison criterions. Analytic hierarchy process was used to find the weighing of comparison criterions according to given points by five experts to each criterions. Final comparison table is formed including all comparison criterions with given evaluation scale points of each alternative fuels, and weighing for each criterion depend on their importance at maritime sector. Methanol and ethanol, liquefied natural gas, and hydrogen get comparison points of 2.129, 4.092 and 3.796 respectively from the total point of 5.005. Comparison shows that methanol and ethanol do not seem to be preferable to use onboard due to their inadequacy which are investigated in the study. Liquefied natural gas gets the highest total evaluation point in the study, and the most suitable alternative fuel. Hydrogen gets the highest point at safety, bunker capability, durability, adaptability to existing ships, and commercial effects criterions. This study shows that hydrogen can be the alternative to liquefied natural gas used as a fuel at ships, but it requires more studies and improvement on the comply with emission regulations and effect on engine components issues.

1. Introduction

Although renewable energies are started to be used, usage of fossil fuels are in a more dominant position. It is more difficult to apply renewable energy systems on transportation sector than land based facilities. As a consequence, fossil fuel use in the transportation sector has a first priority. It is expected that global energy consumption of liquid fuels in the transportation sector will increase to 131 quadrillion BTU on 2040 from 96 quadrillion BTU on 2010 (EIA, 2013). Sea transportation forms the important part of transportation sector, and 90% of world trade is carried across the world's oceans (Harrould-Kalieb, 2008). So it can be said that most part of the global energy consumption of liquid fuels in transportation sector is created by national and international shipping. International Maritime Organization (IMO) states that all ships globally consume 300 million tons of fuel annually (IMO, 2014). Consumed fuels generate huge amount of emissions, which are nitrogen oxides (NO_X), sulfur oxides (SO_X), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM). According to Third IMO GHG Study 2014, annual shipboard NO_X emission on 2012 was 19.002 million tons, SO_X emission was 10.240 million tons, which are 15% and 13% of global NO_X and SO_X emissions, respectively, and CO, CO_2 and PM emissions were 936 thousand tons, 949 million tons and 1.402 million tons on 2012, respective to emission type.

IMO has worked on mitigation and control of the shipboard emissions by international rules and regulations for shipping sector. Limitations for NO_X emission has been entered into force, and from January 1st 2011, Tier II emission limit has been applied outside of Emission Control Areas (ECA), and more strict limitation of Tier III has been applied at ECA region. On and after January 1st 2016, Tier III emission limits will be applied at all regions (IMO Web, 2015a).

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http://dx.doi.org/10.1016/j.jclepro.2015.11.089

Sulfur content of the consumed fuel is the reason of SO_X emission and sulfate formation which is resulted with PM emissions from ships. IMO has limited sulfur content of the fuels. Out of ECA boarders, sulfur limit of fuels was 4.50% prior to January 1st 2012; on and after January 1st 2012, it is reduced to 3.50% until January 1st 2020; and on and after January 1st 2020 (date is not exactly confirmed yet) it will be 0.50%. Inside ECA, sulfur content was 1.50% prior to January 1st 2010; on and after 1 January 2010, it was 1.00% until January 1st 2015; and on and after January 1st 2015 it is 0.10% (IMO Web, 2015b).

In theory when fuel is burnt, CO_2 is composed, and it cannot be prevented to be formed in principle, but it can be decreased by efficient operation. Regulations On Energy Efficiency for Ships in MARPOL Annex VI was entered into force by IMO on January 1st 2013. This regulation aims to control and decrease CO_2 emissions from ships. In this framework, Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) were defined. New building ships have to comply with Required EEDI levels, and existing ships have to have a SEEMP onboard to control and to decrease their CO_2 emissions (IMO, 2011).

It can be seen that stringent rules and regulations are in force, and more strict limitations at outside and inside ECA regions, include the North Sea, the Baltic, and the coastline of North America, are on the way. Additionally, there are some other regions to be ECA, for instance the Bosphorus Strait and Sea of Marmara, Hong Kong, and ports of the coastline of Guangdong in China (Chryssakis et al., 2014). These developments force ship owners and operators to apply emission abatement technologies to their ships.

The emission abatement technologies are exhaust gas recirculation, selective catalytic reduction, SO_X scrubbers, and waste heat recovery systems. Comparison of emission abatement technologies was mentioned in a previous study, and it was stated that these technologies reduces their target emissions, on the other hand they can negatively affect remaining emission types, and also increases fuel consumption (Zincir and Deniz, 2014). In another paper, it was indicated that exhaust gas after treatment systems, such as SO_X scrubbers and urea-based catalysts, are costly and can increase the fuel consumption by 2–3% (Chryssakis et al., 2014). Interest on alternative fuels at marine industry increases as an emission abatement method. Alternative fuel use at marine diesel engines is an option to reduce shipboard emissions nowadays.

In this study, alternative fuels which can be used at marine diesel engines are investigated. Comparison criterions are generated, and new comparison method is developed to find the most suitable alternative fuel which can be used on ships. Hydrogen is offered as a new alternative fuel, and found that it is worth to use as a fuel onboard.

2. Alternative fuels

Alternative fuels which can be used at marine diesel engines are found in two phase; liquid fuels like methanol (CH_3OH), ethanol (C_2H_5OH), bioliquid fuel, and biodiesel; and gaseous fuels like propane, hydrogen and natural gas (Banawan et al., 2009). Remarkable fuels subject to many previous researches are methanol and ethanol in liquid state, and natural gas and hydrogen in gaseous state. Properties of diesel fuel, methanol, ethanol, liquefied natural gas (LNG) and hydrogen are shown at Table 1. The table shows differences between commonly used fossil fuel and alternative marine fuels.

2.1. Liquid alternative fuels

Methanol and ethanol are variety of alcohols which can be produced from renewable sources, by destructive distillation of wood, agriculture products and by reformation process from large quantities of natural gas and coal gas (Yusaf et al., 2013; El Gohary et al., 2014b; Cheng et al., 2008). The characteristics of alcohols are low viscosity, providing easy injection, atomization and better mixture formation with air; less emission due to high stoichiometric fuel–air ratio, high oxygen content, high H/C ratio and sulfur free structure; high evaporative cooling which raises the volumetric efficiency during intake process and compression stroke (Sayin, 2010). On the other hand, it should also be considered that methanol is toxic, corrosive and is twice in volume comparing to marine diesel oil (MDO) (MAN, 2015).

Methanol and ethanol cannot substitute diesel fuel or fuel oil directly, due to their high auto-ignition temperature, low cetane number, high latent heat of vaporization, reduced lubrication potential related to low viscosity (Karabektaş et al., 2013). It is possible to use these fuels in diesel engines utilizing two different ways. One of them is premixed fuel composition of methanol or ethanol with diesel fuel or fuel oil, which does not have any controversial comment in the literature about use with alcohols. The main problem of premixed fuel composition is phase separation of alcohols. The addition of proper solvent is the solution (Karabektaş et al., 2013). The other way is injection of methanol or ethanol separately from diesel fuel or fuel oil. Injection area can change depending on the method applied. At the fumigation method, methanol or ethanol are injected into the intake manifold of the diesel engine; and they are injected into the cylinder from separate injector at the dual-fuel method. Methanol or ethanol ratio is approximately 30–50% at fumigation method, while main fuel is methanol or ethanol, and diesel fuel is used as pilot fuel to ignite main fuel at dual-fuel method (Sarjovaara et al., 2013).

Table 1
Properties of diesel fuel and alternative fuels.

	Diesel	Methanol	Ethanol	LNG	Hydrogen
Density (kg m^{-3})	833–881	798	794	450	0.0838
Auto-ignition temperature (K at 1 bar)	530	743	635	810	858
Flammability limits (vol. % air)	0.7–5	6–36	3–19	4–16	4–75
Stoich. air–fuel ratio on mass basis	14.5	6.5	9.1	17.2	34.3
Net heating value (MJ/kg)	42.5	20.1	27.0	46–50.2	119.9
Flame velocity (cm/s)	30	50	41	380	265–325
Flame temperature (K at 1 bar)	2327	2163	2193	2233	2318
Octane number	30	109	109	120	130
Cetane number	40–55	<5	8	−10	–
Fuel carbon content (wt %)	85	38	52	75	0
Fuel hydrogen content (wt %)	15	12	13	25	100
Fuel oxygen content (wt %)	0	50	35	0	0
Fuel sulfur content (wt %)	<350 ppm	0	0	0	0
References	Zincir and Deniz, 2014; MAN, 2015; Yao et al., 2008; Bromberg, 2008; Demirbas, 2010; Heywood, 1988; Huang et al., 2007; FTA, 1994; Sroka, 2007; Herdzik, 2011; Cheenkachorn et al., 2013; El Gohary et al., 2014a				