Journal of Power Sources 327 (2016) 345–364

Contents lists available at ScienceDirect

Journal of Power Sources

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

Review article

A review of fuel cell systems for maritime applications

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HIGHLIGHTS

- An overview is provided of logistic fuels, fuel processing and fuel cell systems.
- Fuel cell systems are reviewed with regard to maritime power generation requirements.
- The most suitable fuel cell system may depend on a ship's operational requirements.
- Fuel cell application can reduce pollutant emissions from shipping significantly.
- Power density, economics and classification standards need further improvement.

ARTICLE INFO

Article history:
Received 11 March 2016
Received in revised form
1 July 2016
Accepted 2 July 2016

Keywords:
Fuel cells
Logistic fuels
Fuel processing
Ships
Maritime application
Emissions

ABSTRACT

Progressing limits on pollutant emissions oblige ship owners to reduce the environmental impact of their operations. Fuel cells may provide a suitable solution, since they are fuel efficient while they emit few hazardous compounds. Various choices can be made with regard to the type of fuel cell system and logistic fuel, and it is unclear which have the best prospects for maritime application. An overview of fuel cell types and fuel processing equipment is presented, and maritime fuel cell application is reviewed with regard to efficiency, gravimetric and volumetric density, dynamic behaviour, environmental impact, safety and economics. It is shown that low temperature fuel cells using liquefied hydrogen provide a compact solution for ships with a refuelling interval up to a tens of hours, but may result in total system sizes up to five times larger than high temperature fuel cells and more energy dense fuels for vessels with longer mission requirements. The expanding infrastructure of liquefied natural gas and development state of natural gas-fuelled fuel cell systems can facilitate the introduction of gaseous fuels and fuel cells on ships. Fuel cell combined cycles, hybridisation with auxiliary electricity storage systems and redundancy improvements are identified as topics for further study.

1. Introduction

Technology improvements in recent decades have reduced the fuel consumption and environmental impact of ships. However, shipping remains a significant contributor to global emissions of greenhouse gases (GHGs), volatile organic compounds (VOCs), particulate matter (PM), hazardous air pollutants, NO_X and SO_X. It is estimated that shipping activities contribute to 3–5% of global carbon dioxide (CO_2) emissions and over 5% of global SO_X emissions [1]. State of the art propulsion technology in shipping has not kept pace with road transport for various reasons, the most important being the absence of strict regulations on environmental impact at sea [2,3].

With cost of ownership being the main technology driver, economical but polluting diesel engines and cheap heavy fuels have become default choices for maritime power generation. Recently announced regulations are, however, set to change the common practice in maritime power generation. Although eventually postponed to 2021, the international maritime organization (IMO) recently adopted stringent emission limits in its Tier III regulation, most notably on NO_X and SO_X emissions. For emission control areas (ECAs) these requirements are particularly strict and will be difficult to meet with traditional diesel engines and bunker fuels [4]. Ship owners need to adopt solutions to bring exhaust emissions within these and other future limits.

There are several ways to reduce emission levels from shipping.

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http://dx.doi.org/10.1016/j.jpowsour.2016.07.007
0378-7753/

These include: engine improvements, such as exhaust gas recirculation, two stage turbocharging, late miller timing, smart combustion chamber design and advanced fuel injection systems [5,6]; exhaust gas aftertreatment, like scrubbers or selective catalytic reduction; and finally the use of different bunker fuels, for example low sulphur diesel or liquefied natural gas (LNG) [7–9]. A combination of these methods will be required, and this is likely to increase size, complexity, fuel consumption and maintenance of maritime power plants [10]. Therefore, clean and efficient alternatives for internal combustion engines are highly desired.

Among the possible alternatives, fuel cells are considered to be one of the most promising future technologies [11]. Fuel cell systems for residential applications have proven their ability to produce electricity with lower heating value (LHV) efficiencies up to 60% using natural gas (NG) [12]. Efficiencies over 70% are projected when they are combined with gas turbines or reciprocating internal combustion engines [13–15].

Fuel cell technology prospects have motivated several studies to assess the potential and applicability of such systems in the maritime environment. In addition, a number of demonstrator systems has been developed and tested on ships. These investigations vary from a feasibility study of various diesel-fuelled fuel cell systems [16], to a commercialised, hydrogen fuelled, air independent propulsion (AIP) system for submarines [17]. Whether fuel cell systems will be applied more general in the maritime environment depends on their ability to meet the requirements of on-board power generation.

Fuel cell systems differ substantially from each other, and it is not clear which system has the best future prospects. An overview of fuel cell systems is provided in this review. Then, various fuel cell systems are evaluated according to important performance criteria for maritime application: fuel consumption, power and energy density, load-following capabilities and environmental impact. Finally, safety and economics are briefly discussed.

2. Fuel cell systems for ships

Electrical power in ships is mainly used for auxiliaries, although there is a tendency towards the use of electricity for propulsion as well. For example in hybrid configurations, and in the *all-electric ship* concept, where advanced electrical propulsion techniques and electrical storage components can be used [18,19].

A vast majority of ships currently uses diesel generators to produce electricity, where chemical energy is converted into electricity via thermal and mechanical energy. In contrast, fuel cells convert chemical energy directly into electrical energy, thus omitting the indirect route via thermal energy in combustion engines. The absence of expansive, high temperature combustion reduces NO_X formation, noise and vibrations, while high efficiencies can still be achieved [20].

Just like batteries, fuel cells are modular in nature and the intrinsic performance of a single cell is not different from a large stack [21]. As a result, power production can be distributed over the ship without a penalty of increased fuel consumption, while electricity transport losses are reduced and redundancy is improved. For this reason, fuel cell systems are successfully applied in back-up power systems and data centers [22]. Furthermore, fuel cell systems have good part load characteristics, since increased mechanical losses affect only the parasitic load of the auxiliary components, such as compressors, while electrochemical losses are reduced [12,23].

The selected fuel cell system and logistic fuel will have a large impact on the suitability for maritime application. Therefore, the implications of fuel cell system choices on overall efficiency, complexity and power density are analysed in this section. Commonly applied fuel cell types, fuelling options and fuel processing equipment, used to convert various logistic fuels into hydrogen rich gas, are discussed.

2.1. Fuel cell types

A variety of fuel cell types with distinct characteristics has been developed. The low and high temperature polymer electrolyte membrane fuel cell (LT/HT-PEMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) will be considered in this review and are briefly introduced. Some relevant characteristics are summarised in Table 1.

The LT-PEMFC has known rapid development in the last decades, and achieved high power densities and good transient performance. Its membrane consist of a proton conducting wetted solid polymer [24]. The necessity of a wet membrane, while the gas-diffusion pores have to remain dry, dictates an operational temperature of 65–85° C and complicates water management [25]. At low temperatures, the use of platina is required to catalyse the electrochemical reaction [26]. Another important disadvantage of the low operational temperature is the limited tolerance to fuel impurities. In particular carbon monoxide (CO) deactivates the catalyst, because of its strong surface adsorption at low temperatures [27,28].

The membrane of the PAFC consists of a silicon carbide matrix saturated with liquid phosphoric acid. The higher operating temperature, 140 to 200° C, reduces the required platinum loading and increases CO tolerance. The low power density and durability issues have so far limited the commercial success of the PAFC. A new membrane operating in the same temperature region has been developed in the past decade in an attempt to overcome these issues. This membrane essentially combines a polymer electrolyte and phosphoric acid membrane, and is therefore known as the high temperature (HT)-PEMFC [29,30].

Platinum can be replaced with cheaper catalysts, such as nickel, in the high temperature fuel cell classes. Furthermore, CO becomes a fuel rather than a contaminant to the fuel cell. Another advantage is the opportunity to use high temperature waste heat and steam, for example in a bottoming cycle or for fuel processing. The MCFC is a relatively mature high temperature fuel cell and operates in a range of 650–700° C. MCFCs are commercially available, but still struggle with high cost, limited life time and low power density [31,32].

The SOFC has been heavily investigated during recent decades, and various classes of SOFCs have been developed over the years, with operating temperatures ranging from 500 to 1000° C. The low temperature classes are mainly applied in stand-alone fuel cell products, with electrical efficiencies up to 60% [12,33], while the high temperature SOFCs are targeted for combined operation with gas turbines, where efficiencies over 70% are projected [13]. Although a promising type, their limited development state, mechanical vulnerability and high cost have so far limited wide-spread adoption of SOFC technology [34].

2.2. Balance of plant components

Auxiliary components are required to generate electrical power with a fuel cell stack. These components are usually referred to as the balance of plant (BoP), and make up a large part of the overall system. A distinction can be made between *hot* and *cold* BoP components in high temperature fuel cell systems and systems with fuel processing equipment. Hot BoP components include, for example, heat exchangers and fuel processors, while power conditioning and system controls are classified as cold parts. Many BoP components consume parasitic power and additional fuel.