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Solid oxide fuel cell/gas turbine trigeneration system for marine applications

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ABSTRACT

Shipping contributes 4.5% to global CO_2 emissions and is not covered by the Kyoto Agreement. One method of reducing CO_2 emissions on land is combined cooling heating and power (CCHP) or trigeneration, with typical combined thermal efficiencies of over 80%. Large luxury yachts are seen as an ideal entry point to the off-shore market for this developing technology considering its current high cost.

This paper investigates the feasibility of combining a SOFC-GT system and an absorption heat pump (AHP) in a trigeneration system to drive the heating ventilation and air conditioning (HVAC) and electrical base-load systems. A thermodynamic model is used to simulate the system, with various configurations and cooling loads. Measurement of actual yacht performance data forms the basis of this system simulation.

It is found that for the optimum configuration using a double effect absorption chiller in Ship 1, the net electric power increases by 47% relative to the electrical power available for a conventional SOFC-GT-HVAC system. This is due to more air cooled to a lower temperature by absorption cooling; hence less electrical cooling by the conventional HVAC unit is required. The overall efficiency is 12.1% for the conventional system, 34.9% for the system with BROAD single effect absorption chiller, 43.2% for the system with double effect absorption chiller. This shows that the overall efficiency of a trigeneration system is far higher when waste heat recovery happens.

The desiccant wheel hardly reduces moisture from the outdoor air due to a relative low mass flow rate of fuel cell exhaust available to dehumidify a very large mass flow rate of HVAC air, Hence, desiccant wheel is not recommended for this application.

1. Introduction

1.1. Shipping emissions

Shipping emissions are not covered by the Kyoto Agreement. According to the latest United Nations International Maritime Organisation report [1], shipping emitted 1.046 billion tonnes of CO_2 in the year 2007, and thereby contributed 3.3% of global CO_2 emissions. If no further actions are taken, it is concluded that shipping greenhouse gas emissions could increase by up to 250% by 2050. In addition, due to the lack of current regulations in shipping emissions, the most polluting "bunker fuels", with significantly more sulphur than road diesel, are being used as fuel, generating significant SOx emissions [2].

1.2. Harbour and sea regulations

Ships pollute when docked and left idling. According to a study by Corbett et al. [3], particulate matters from ocean-going ships cause about 60,000 deaths a year from heart and lung-related cancers, with most deaths occurring in Europe, East and South Asia near the coastlines.

As a result, new and stricter regulations are being developed for ports. In late 2007, the Los Angeles and Long Beach ports in the United States started to require ships to turn off all on-board power systems when docked, using plugged in electrical systems instead [4]. Stricter regulations regarding emissions in a wide range of sea areas are expected in the foreseeable future. Hence, it will be necessary to reduce the current level of emissions in order to be allowed to enter these restricted areas.

In Europe, particularly sensitive sea areas (PSSAs) have been designated in most parts of the sea, including the Western European Waters and the Baltic Sea areas. PSSA is defined by the International Maritime Organisation (IMO). The provisions of the United Nations Convention on the Law of the Sea (UNCLOS) are

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relevant in the areas. In a PSSA, specific measures can be used to control the maritime activities in that area, such as routing measures, strict application of MARPOL (International Convention for the Prevention of Pollution from Ships) discharge and equipment requirements for ships, such as oil tankers; and installation of vessel traffic services [5].

Since August 2006, the European Union has implemented regional level regulation in the form of SOx emission control areas (SECAs), where the maximum sulphur level in marine fuels is set at 1.5%, which is one-third of the maximum level stipulated by the IMO International Convention on the Regulation of Air Pollution from Ships (MARPOL Annex VI) [6]. European SECAs include the North Sea, the Baltic Sea, and the English Channel. This means that more expensive and cleaner fuel (distillate) needs to be used. However, the Annex at this stage allows the use of marine diesel oil, as long as an approved exhaust gas cleaning system or any other verifiable technological method is fitted to a ship to reduce SOx to the required level.

Over the long term, SECAs will not be enough to reduce SOx emissions. The Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) amended the MARPOL Annex VI regulations in October 2008. The main changes will see the global sulphur limit to be reduced (from the current 4.5%) to 3.5% by January 2012; and progressively to 0.5% by January 2020, subject to a review to be completed by 2018.

In July 2010, the sulphur limit at SECAs was reduced to 1.0%; with further reduction to 0.1% from January 2015.

Further, in January 2010, a maximum 0.1% sulphur limit was in place for inland waterway vessels and ships at berth in all European Community Ports. The alternative will be to use approved exhaust gas cleaning system and/or use shore side power supplies.

Besides SOx emissions, NOx emissions levels regulation has been revised and tightened as of October 2008. The new regulation follows a 3-tier approach. Tier I applies to diesel engines installed in ships built between January 2000 and January 2011. Tier II applies to new ships built on and after January 2011. Tier III applies to new ships built on and after January 2016, operating at Emissions Control Areas. The emissions limits in each tier vary with the engine revolutions per minute (rpm).

Should an upgrade kit be available, NOx standards will retroactively apply to existing ships built from 1990 to 2000 with engines >5000 kW and ≥90 l displacement [6].

Moreover, incorporating shipping into a global carbon dioxide emissions trading scheme or charging a climate levy on bunker fuel are efficient and cost effective in delivering emissions reductions, and likely to be introduced in the 2012 post-Kyoto climate regime [1].

In addition, the Shipping Emissions Abatement and Trading (SEAaT) has carried out a Sulphur Emissions Offsetting Pilot Project, to explore the application of emissions trading for reducing sulphur emissions from shipping activities [7].

Due to the increasing regulations, ship owners are encouraged to seek ways to increase energy efficiency and reduce consumption of fuels onboard.

1.3. Marine fuel cell-gas turbine system

The most common power source on board of luxury yachts as well as other seagoing vessels is the diesel generator. The diesel generator has a good ratio of available power to mass and volume.

The demand for available power is steadily increasing and ever larger engines with high power outputs are being installed. However, diesel engines produce noise and vibrations as well as emissions such as NOx, SOx and particulates. In order to minimise noise and vibrations, shock absorbers and other passive means are used to reduce the propagation of noise and vibrations within the vessel. These passive provisions are cost intense and additional weight is added to the ship.

In order to reduce fuel consumption and emissions, one option is to replace some of the existing diesel generators with a solid oxide fuel cell (SOFC). The noise and vibration level on board can also be reduced significantly.

The power demand of a yacht depends on its mode of operation. Most electrical power is required when the electrically powered auxiliary drives, like stern and bow thrusters or pump jets, are used. These drives are used in manoeuvring or dynamic positioning mode. The modes of operation are not bounded to any fixed schedule but depend on the habits of the owner.

Due to the relatively new technology of the fuel cell, the long start-up and stopping time (typically 18–30 h on average) and limited load following capability, fuel cells are only operated at constant power output to meet base load demands. This means that the fuel cell system is only an auxiliary power unit (APU).

The minimum average load occurs in harbour operation. The base load of a mega yacht is in the range of 15–25% of total installed electrical power. Small load fluctuations will be compensated by an energy storage system or a gas turbine system. Additional load during the sea mode and manoeuvre mode can be provided by the conventional diesel generators, operating in parallel to a fuel cell system [5].

Past papers have only discussed the application of a 300 W proton exchange membrane fuel cell with reforming for sailing yacht application [8]; and a 500 kWe Molten carbonate fuel cell system with diesel reforming for cruise, passenger or commercial ship [9].

1.4. Choice of fuel for marine SOFC-GT systems

The choice of fuel for the powering of a fuel cell system onboard the yacht depends on the available technologies for fuel cells and the fuel production pathways, limited by the restriction of fuel and fuel quality for shipping.

The following shows the pros and cons of fuel available from each production pathway; and the safety and requirements as a fuel for a fuel cell system.

1.4.1. Hydrogen

Although hydrogen itself is a compatible fuel with the majority of fuel cell systems, it is impractical to use as a primary shipping fuel, due to:

- Relative low power density (i.e., large volume requirements)
- Lack of supply infrastructure
- Only relevant for applications with low power and frequent refuelling opportunities (i.e., ferries, inland water vessels, coastal vessels) [39].

1.4.2. Liquid hydrocarbons

In general liquid hydrocarbons have significant advantages over hydrogen for energy storage onboard the yacht, namely:

- Relative high power density
- Supply infrastructure is available (at least for marine diesel oil or marine gas oil) or possible with “moderate” investments being established
- Relevant for high power applications without frequent refuelling opportunities (i.e., all other seagoing ships) [39].

1.4.3. Diesel

The use of shipping diesel is the preferred option given the existing infrastructure of many shipyards. Yacht owners would usually try to run the engines with high quality fuel. These fuels have a sulphur content of approximately 0.2–0.5%, which significantly