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Comparative efficiency and environmental impact assessments of a hydrogen assisted hybrid locomotive

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ABSTRACT

The integration of more environmentally benign fuel options for mass transportation applications is a critical research initiative, particularly those that support and further development toward a hydrogen economy, a key target for future sustainability. The thermodynamic and environmental performances of a hydrogen assisted hybrid locomotive with ammonia-diesel co-fueling are comprehensively assessed through energy and exergy analyses, and impact assessment. Onboard hydrogen production via thermal ammonia decomposition (cracking) utilizes exhaust gases as a heat source, reducing the total diesel fuel consumption and increasing energy utilization of the fuel burned in the locomotive prime mover engine. The hybrid system performance is compared against a conventional diesel-electric locomotive through energy and exergy efficiencies, fuel consumption, and environmental impact to evaluate the viability of the hybrid locomotive as a clean rail transportation option.

Introduction

The environmental impacts of fossil fuel consumption are a global concern; in particular, GHG and harmful CAC emissions associated with fossil fuel combustion. According to 2013 data presented by the Intergovernmental Panel on Climate Change (IPCC) [1], 28% of Canada's total GHG emissions were the result of fossil fuels consumed by its transportation sector. The majority of these GHG's are associated with on-road passenger and freight vehicles—i.e. cars, light to heavy duty trucks—highlighting the need to explore practical solutions integrating more environmentally benign mass transit options for both passenger and freight transport.

Rail transit offers an efficient alternative to passenger vehicles (cars), with existing, operational infrastructures in urban and suburban centres across Canada and internationally. In the best case scenario, trains are considered a convenient and affordable option in place of cars and other light vehicles with the ability to quickly and efficiently move a high volume of commuters. Furthermore, adoption of commuter trains for daily passenger transit has the potential to reduce traffic congestion and the related wear and tear on road surfaces, particularly in high-population urban centres. Though able to effectively reduce traffic congestion and pressures on

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road infrastructures, locomotives still rely on fossil fuel; while rail transit, in the context of Canadian economic sectors as a whole, represents only a small portion of total GHG emissions (~1% of total GHGs in 2012, according to Environment Canada [1]). In conjunction with this, the significant role of fossil fuel combustion in releasing harmful emissions, makes the investigation and implementation of viable and environmentally benign alternatives worthwhile.

Clean fuels and energy resources have a key role in both short and long-term sustainable development of transportation. Ammonia (NH_3) is the only carbon-free chemical energy carrier besides hydrogen that is suitable as a transportation fuel [2]. In addition use as a fuel, NH_3 is a hydrogen energy carrier, and is widely used as a NO_x reducing agent for combustion exhaust gases using selective catalytic reduction (SCR), and its capacity as a refrigerant can be applied to recover and utilize engine heat that would otherwise be lost. In terms of environmental sustainability, NH_3 can be produced from fossil fuels or any renewable energy source, using heat and/or electricity [3], which allows for evolution of NH_3 production methods and technologies in parallel with sustainable development.

Hydrogen (H_2) is widely seen as the ideal fuel for sustainable development, with the highest gravimetric energy content and no pollutants in its combustion products. The primary process for producing H_2 is steam-methane reforming (SMR) of non-renewable natural gas resources; however, synthetic natural gas options offer a means of transitioning toward more sustainable options as renewable energy technologies gain maturity. Before society can realize the hydrogen economy, certain challenges require innovative solutions. Most significantly, is the development of efficient storage methods; as the lightest element, hydrogen requires either large volumes, high pressure, low temperature, or advanced material storage techniques carry sufficient fuel supply for a practical operating range [4]. The characteristics of storage options are given in Table 1.

Ammonia has been considered as an alternative transportation fuel for over 70 years [6], and is an important nitrogen source in agricultural and industrial applications. There are two ways to utilize NH_3 as a transportation fuel: ICE engines, and fuel cell systems. This study addresses ICE applications for NH_3 fuel, integrating direct feed or a combination of direct feed and decomposition options for NH_3 and H_2 fuel utilization, with additional options detailed in [5] and [6]. Comparison of the energy densities of traditional and alternative fuels is shown in Fig. 1. Although the low volumetric energy density of ammonia (relative to traditional hydrocarbon fuels) presents a challenge for implementation in passenger vehicles as a direct feed combustion fuel—requiring over two times the volume of diesel fuel or motor gasoline for the same amount of energy—heavy duty on- and off-road vehicles such as locomotives and freight trucks are well equipped to carry the additional fuel weight without becoming prohibitive for the vehicles' performance.

One of the significant considerations when comparing alternative fuels is their potential to reduce high levels of GHGs and other hazardous emissions harmful to health and the environment. The carbon–hydrogen ratio of various transportation fuels is shown in Fig. 2. Although biodiesel has a carbon content similar to petroleum diesel, the carbon combustion products are largely neutral depending on the fuel feedstock.

Ammonia has the highest hydrogen energy density in comparison to other combustion fuels—even exceeding that of pressurized and liquefied H_2 based on current storage methods [9],—is carbon-free, zero global warming potential (GWP), and produces only nitrogen and water for complete combustion.

This paper evaluates a hybrid locomotive option that integrates ammonia fueling and thermal decomposition in a modern diesel-electric locomotive. Waste heat recovery from exhaust gas supplies thermal input for ammonia decomposition to produce hydrogen for combustion assistance, and improves the overall energy utilization of the hybrid locomotive system. Thermodynamic and environmental impact assessments are conducted to compare the performance of the conventional and hybrid locomotive options and highlight the potential of ammonia and hydrogen as alternative fuels for clean rail applications, and environmental impact reduction for the transportation sector.

System description

The operating characteristics of the locomotive prime mover engine and cooling systems are tabulated in Table 2, and they are used as input values for system analyses and assessments. The baseline system is shown schematically in Fig. 3, for a conventional diesel-electric locomotive powered by a large two-stroke compression ignition diesel engine supplied with ULSD fuel. During operation, intake air undergoes compression by a given ratio, pr_{TC}, in the turbocharger compressor. Aftercooling in HX-ac increases the density, and therefore the mass flowrate, of the intake air entering the engine cylinders. Following internal combustion and expansion, exhaust gases pass through the turbine (T1) of the turbocharger, which drives the rotor of compressor C1, and then exhausted.

Table 1 – Comparison of hydrogen storage methods.

Storage method	Energy intensity (MJ/kg-H_2)	wt%-H_2/tank	wt%-H_2/kg-system	g-H_2/tank	g-H_2/L-system
Compressed H_2 (35 MPa)	10.2	6	4–5	20	15
Liquid H_2	28–45	20	15	63	52
Low temperature hydrides ($T < 100$ °C)	10–12	2	1.8	105	70
High temperature hydrides ($T > 300$ °C)	20–25	7	5.5	90	55

Source: [5].