A Hybrid Marine Vessel – Supplemented by a Thermoelectric Generator (TEG) Power System – as a Case Study for Reducing Emissions and Improving Diesel Engine Efficiency

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Abstract: A hallmark of the maritime transportation industry is efficiency. Estimates are that 90% of cross border world trade is accomplished by means of waterways while consuming only 7% of the energy for the total transportation sector. Nonetheless, marine diesel engines, which serve as power plants for most commercial, ocean going vessels, have long been identified as a major source of air pollution for port cities and coastal areas. Accordingly, the International Convention for the Prevention of Pollution from Ships (the MARPOL Treaty) has significant ramifications for the maritime industry, as exemplified by the stringent 2016 standard to lower emissions. Such realities, along with the rising cost of non-renewable petroleum fuels, necessitate the recovery of the wasted heat onboard marine vessels. Thermoelectric materials are an enabling technology that allows the recapture of this wasted energy from heat sources, such as exhaust and coolant systems, which account for nearly 50% of the total combustion energy. If a fraction of the marine diesel's wasted energy could be harnessed and stored with high power density batteries, an electric drive system could be utilized to transport ships quietly and cleanly into and out of congested ports and high population centers. Overall, a dramatic reduction of the maritime industry's carbon footprint could be realized, as a modest 10% increase in engine efficiency translates into a savings of approximately 180,000 barrels of fuel per day on a world-wide basis.
Solid state thermoelectric materials, when exposed to a thermal gradient, generate an electric potential according to the Seebeck effect. While the automobile industry has taken a lead in commercializing thermoelectric generators (TEG) as early as 2013, it is the marine industry that may well be the greater beneficiary of this technology.

Economies of scale, the ability to generate a higher thermal gradient, and fewer weight and volume constraints, all suggest a promising feasibility for marine applications. The successful development of a hybrid thermoelectric vessel (green ship) at Maine Maritime Academy is a promising first step in helping realize the theme of this year's General Assembly of the International Association of Maritime Universities (IAMU): Green Ships, Eco Shipping, and Clean Seas.
Keyword: thermoelectric, generator, hybrid, emissions, marine, diesel, efficiency

1. INTRODUCTION TO THE GLOBAL ENERGY CHALLENGE

According to the United States Energy Information Administration (USEIA), the world's consumption of oil and petroleum products is approximately 84 million barrels per day in 2009 [1]. The USEIA also forecasts a 49% increase in world marketed energy consumption by the year 2035, with much of that growth attributed to developing countries who are currently not members of the Organization for Economic Cooperation and Development, i.e. non-OECD. By 2035 liquid fuels will remain the largest source of energy. As fuel prices rise and alternative energy sources are developed, however, an anticipated decline of the liquids' share of world marketed energy consumption will fall from 35 percent currently to 30 percent in 2035. No foreseeable decline in dependence of liquid fuels is projected for the transportation sector, unless a significant technological advance is realized in improving engine efficiency [2]. The scope of this paper presents a solution to the energy challenge in the maritime transportation industry with the development of a thermoelectric waste heat recovery system.

2. AN ECONOMIC LENS ON THE MARITIME INDUSTRY

As trade among nations grows, the volume of freight transported by both air and marine vessels will increase. Consequently, a greater demand will be placed on the one sector which is expected to increase its reliance on liquid fuels – transportation. Pursuant to the theme of the 12th Annual General Assembly of the IAMU *Green Ships, Eco Shipping and Clean Seas*, let us analyze both the contribution of the maritime industry to the energy equation, as well as the anticipated benefits of employing a thermoelectric waste heat recovery system for the purpose of improving diesel engine efficiency.

According to researchers at Hofstra University, the economies of scale for the maritime industry qualify it as the most efficient mode of transportation. Marine vessels accommodate 90% of cross-border world trade while consuming only 7% of the total energy in the transportation sector [3]. By utilizing the aforementioned USEIA data tables – which allocate 30% of total energy consumption to the transportation sector – one can estimate the daily energy consumption for the maritime industry at 1.8 million barrels per day. As the demand for liquid fuel is generally inelastic with respect to price, shipping companies typically realize savings and reduce emissions by decreasing travel speed through slow steaming (20 knots) and super-slow steaming (12 knots) [4]. Lower speeds reduce drag forces thereby improving fuel economy. Notwithstanding the obvious impact to travel times and scheduling port of call visits, slow steaming is not the long-term elixir for high energy prices; the imperative for investing in more efficient ships is critical to meeting more stringent environmental regulations that are forthcoming.

In summary, while the efficiency of maritime transport is unrivaled by other modes, a technical perspective on the lost opportunity is warranted, not only to quantify that potential cost savings to the shipping industry but also to help prepare it for the foreseeable challenges outlined in the USEIA analysis. And so, one may naturally ask whether an enabling technology does exist by which a marginal increase of 10% efficiency in a marine diesel engine would result in an additional savings of 180,000 barrels per day. With geopolitical tensions in the Mideast and Northern Africa driving the price of oil over $100 per barrel, this 10% increase in power plant efficiency equates to an annual savings of $6.5 billion for the maritime industry.

3. ENVIRONMENTAL IMPACT

During the internal combustion process, approximately 50% of the total energy is lost to exhaust emissions, coolants, and internal friction, as illustrated below in Figure 1.

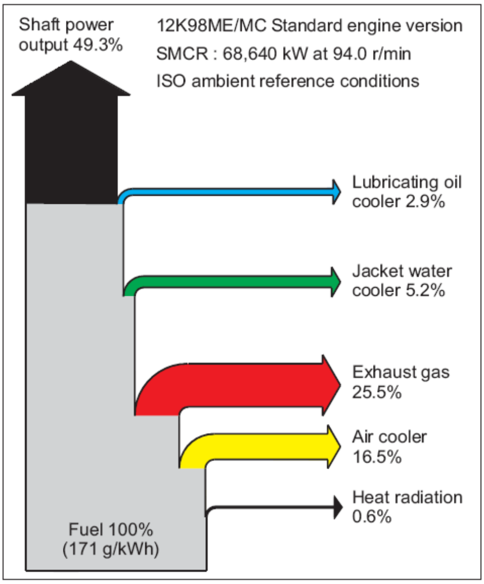

Figure 1. Marine Thermoelectric Heat Sources (Courtesy MAN/B&W Thermal Efficiency System)

The environmental impact, and resulting indirect cost to human life and coastal regions, is staggering. According to a comprehensive, epidemiological study of mortality from ship emissions, J. Corbett et al. conclude that the 1.2-1.6 million metric tons of particulate matter emanating from oceangoing ships are responsible for 60,000 cardiopulmonary and lung cancer deaths annually [5]. Moreover, 70% of those ship emissions occur within 400 kilometers of land. Their research further projects an escalation of the mortality rate concomitant with the increasing demand for liquid fuels and the growth of the shipping industry.

Such an environmental reality, coupled with the aforementioned economic forces, necessitate an innovative approach to designing the next generation of green ships. Reducing the maritime industry’s carbon footprint will not only place it in compliance with the MARPOL treaty, but the approach makes a cogent business case as well. This technology development would augment the efficiency of a marine diesel engine, while simultaneously employing a hybrid propulsion system that would greatly mitigate emissions in ports and near coastal areas.

4. A GREEN SHIP SOLUTION

In 2010, a research team, comprised of Maine Maritime Academy (MMA) and the University of Maine (UMaine), designed and fabricated a unique, thermoelectric hybrid vessel from an encapsulated lifeboat to serve as a dedicated test platform. The lifeboat was retrofitted with a new diesel electric propulsion system featuring a C2.2 Caterpillar genset and a 22 kW electric motor. In order to meet the requirements of hybrid classification, the energy recovered by the thermoelectric generator (TEG) is reintroduced into the propulsion system thereby reducing the load on the generator set. Conversion of the variable DC output of the TEG to a stable AC source was accomplished with a specialized micro-inverter that accepts the low voltage DC, converts it to AC, and acts as a transformer by stepping up the voltage to a higher and more practical level for usage onboard ships. By the end of the summer of 2010, this hybrid vessel made her maiden voyage in a cruise around the harbor in Castine, Maine. An illustration of MMA's hybrid "Green Ship" is depicted below in Figure 2.

Figure 2. Maine Maritime Academy's Hybrid "Green Ship" Prototype

A complete technical description of MMA's green ship system is provided by Sarnacki et al. [6]. This research and development is noteworthy in a number of directions, not the least of which is the realization that the maritime industry may well be the greater beneficiary of this technology vis-à-vis the automotive industry which too is actively working to commercialize TEGs as early as 2013. In comparison to motor cars, ships are not as encumbered by size, weight and cost of a TEG system. Then, one must consider that the ability to generate electricity from a waste heat source is directly a function of the temperature gradient between the exhaust stream and a coolant. Here too, the maritime industry holds an unprecedented advantage in the differential existing with respect to the bountiful ocean, whose temperatures are well below that of any automotive coolant. Lastly, retrofitting existing ships with TEGs is a feasible option.

5. CASE STUDY FOR R&D MODEL AT IAMU

In the United States, a clarion call is sounding for institutions of higher learning to embrace and to integrate research and development (R&D) in some form within the undergraduate experience. The consequence of this trend has many implications for redefining the mission statement of a college or university. Maine Maritime Academy, like many of her counterparts within the International Association of Maritime Universities (IAMU), is primarily a “teaching institution.” Yet today, few could argue effectively against the tangible benefits that this student-centered, and mission-specific, R&D has had in both enhancing the quality of teaching and augmenting the relevancy of the institution in the state and national economy.

The hybrid vessel, marine thermoelectric program at MMA serves as a successful case study for encompassing R&D into the curriculum of an IAMU institution. What began in 2009 as co-author Wallace’s engineering capstone project has now grown into an on-going effort involving several engineering faculty, a chemistry professor, and numerous undergraduates. Working in design teams, these students have garnered first place prizes in paper competitions sponsored by the Society of Naval Architects and Marine Engineers held on the campus of the Massachusetts Institute of Technology.

To illustrate the nexus with industry and graduate education, Mr. Wallace, a 2009 MMA graduate in Marine Systems Engineering, has matriculated to an M.S./Ph.D. program at the nearby University of Maine where he has also demonstrated the entrepreneurial spirit by founding Thermoelectric Power Systems, LLC. Within a short period of time, his Company has garnered financial support from the Libra Foundation and has received a Small Business Technology Transfer (STTR) contract from the Department of Defense.

6. CONCLUSIONS AND FUTURE WORK

Maine Maritime Academy has successfully designed and built the first-of-its-kind hybrid marine vessel utilizing a thermoelectric generator for waste heat recovery. To accommodate the greater capacity of marine diesel engines, Thermoelectric Power Systems LLC, along with its partners at MMA and UMaine, is now designing and developing a TEG specific to maritime applications with a reliability to withstand the harsh operating environments. While the existing 180 watt TEG employed the reliable, benchmark material, bismuth telluride, the research team is now actively collaborating with materials developers who are reporting 20% conversion of thermal energy into electricity [7]. Realization of these gains will be a monumental achievement in both maritime emissions reduction as well as improvement in diesel engine efficiency.

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