RECENT DEVELOPMENTS IN LIQUEFIED NATURAL GAS AS A MARINE FUEL

Introduction:

In the global push towards cleaner alternative fuels, the issue of marine fuel has come under scrutiny. International maritime trade plays an integral role in the global economy, with over 80% of global merchandise trade ferried through sea routes[1]. However, transportation ships are very destructive to the environment. Cargo ships have historically relied on fossil fuels for power, beginning with the advent of steam-powered ships that burned coal as a fuel source[2]. Further iterations have moved away from coal and towards crude oil extraction, with current freighters operating with a wider variety of fuels. Heavy fuel oil (HFO) is the primary fuel of the shipping industry[2], which generates harmful greenhouse gases (GHGs) that contribute to global warming and cause health problems when inhaled[2].

Further compounding the issue of fuel efficiency is the size of modern cargo ships, which is perpetually increasing to carry more volumes of cargo and thus requires more tons of fuel to travel[3], as indicated with the CMA CGM Benjamin Franklin and its fuel consumption rate as shown in Figure 1. While fuel usage can decrease with a drop in ship speeds[3], that drop is offset by the sheer volume of cargo ships operating simultaneously. As of 2022, international maritime transport is one of the most significant contributors to pollution, accounting f or roughly three percent of global greenhouse gas emissions[4].

While previous alternatives have emerged addressing the volume of GHG production, notably the emergence of low sulfur fuel oil which mitigates these emissions, they are more expensive and produce nitrogen oxide (NOx), a more potent GHG than carbon dioxide (CO_2)[2]. From this climate, liquefied natural gas (LNG) has emerged as the most commonly used alternative fuel in the marine industry5. A cheaper fuel than HFO, LNG has a lower concentration of sulfur, carbon, and nitrogen, further reducing emissions by nearly 75%5. While a strong contender in its own right, LNG is restricted by a high cost to retrofit compatibility for existing vessels and a shortage of LNG facilities in ports[5]. Regardless, liquid natural gas is a promising alternative to marine fuels, and it has been the concentration of many developments and innovations in the past five years. This article explores the unique qualities of LNG and recent developments regarding the fuel that promise to bolster the efficacy and efficiency of LNG in the future.

Figure 1: The CMA CGM Benjamin Franklin, one of the largest cargo ships to ever visit the U.S. An ultra-large container ship measuring 399.2 m in length, 54 m in width, and 60 m in height. The vessel carries 4.5 million gallons of fuel oil and consumes 330 tons of fuel daily[3].

LNG Aging:

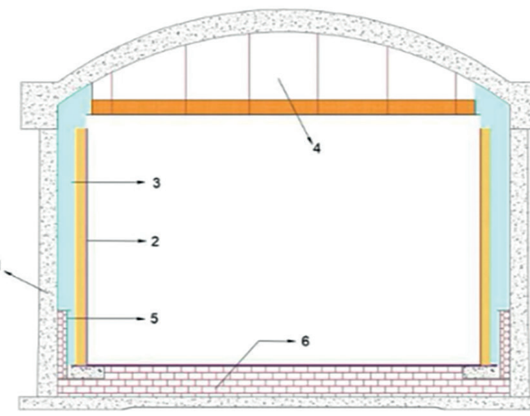
A significant issue with LNG comes from storage. As the name implies, LNG is natural gas cooled to a liquid state to shrink its volume and facilitate easier transportation[6]. The main component of natural gas is methane (CH_4), which cannot be liquefied through pressurization like gasoline or other hydrocarbons. To ensure the fuel remains a liquid, transporting ships employ a cryogenic insulation design that keeps the LNG near boiling point at a fixed atmospheric pressure[7]. However, due to imperfect insulation and random fluctuations, a portion of the fuel will evaporate into its gaseous phase, producing a boil-off gas (BOG)[7]. This process is known as LNG aging, and the effects of which will fluctuate depending on the composition of the individual LNGs. As this process inevitably alters the properties of the fuel, as more volatile gases have higher boiling points, LNG aging must be considered[7].

To control the rate of daily evaporation and boost long-term storage capability, the insulation system is paramount. Thus, a research group from the China National Offshore Oil Corporation (CNOOC) posted a 2023 study that analyzes and optimizes the design of an insulation system for large LNG storage tanks, considering various design parameters and establishing an ideal daily evaporation rate for future reference in similar systems8. Firstly, the study identifies the storage tank, its insulation system and BOG exportation system, and the structure and composition of its tanks and walls[8]. As an example, the study uses a 30,000 m3 storage tank constructed as shown in Figure 2. The article then identifies that, as LNG heat exchange per volume decreases with an increase in storage tank volume, larger tanks will naturally experience a decreased daily rate of evaporation[8].

Next, the team calculated the necessary cryogenic material cost during the construction of all materials used in the tank and operation cost under several daily evaporation rates, remarking that the prices are taken from domestic project rates. The results are documented in Table 1. Finally, after analyzing the cost of construction, operation, and the expenses incurred from venting excess BOG during operations, as totaled in Figure 3, the team concluded that for a 30,000 m^3 LNG storage tank, the maximum allowable daily evaporation rate should be 0.08 wt%/day[8]. While seemingly inconsequential for current stores, future LNG storage tanks can use this maximum rate as a reference for construction costs. Production systems could factor in the long-term costs and balance budgets accordingly. If this standard is widely adopted, large LNG tanks will be more homogenized, increasing the efficiency of LNG transportation and storage while reducing production costs from overspending to account for evaporation.

Catalytic Reduction Systems:

Additionally, further developments and frameworks are emerging to tackle a significant flaw in LNG products. While LNG emits roughly 25% less CO_2 compared to conventional fuels[9], it is also a carrier of another GHG. As previously stated, LNG is mostly CH_4, which is more potent than CO_2 and has a higher potential to trap heat in the atmosphere. While liquefied natural gases emit less CO_2, their potential to release methane is a strict disadvantage. Existing regulations such as the MARPOL Convention and the IGF Code have systematically limited pollution rates on freighters[10], but the pollution rates of the fuel itself can also be kept in check.



1) Prestressed concrete outer tank; 2) 9% Ni steel inner tank; 3) Insulation layer of tank wall (inner elastic felt + outer expanded perlite); 4) Ceiling glass wool insulation layer; 5) TPS insulation layer (foam glass brick); 6) Bottom insulation layer (foam glass brick)

Figure 2: The structural diagram of a typical LNG storage tank[8].

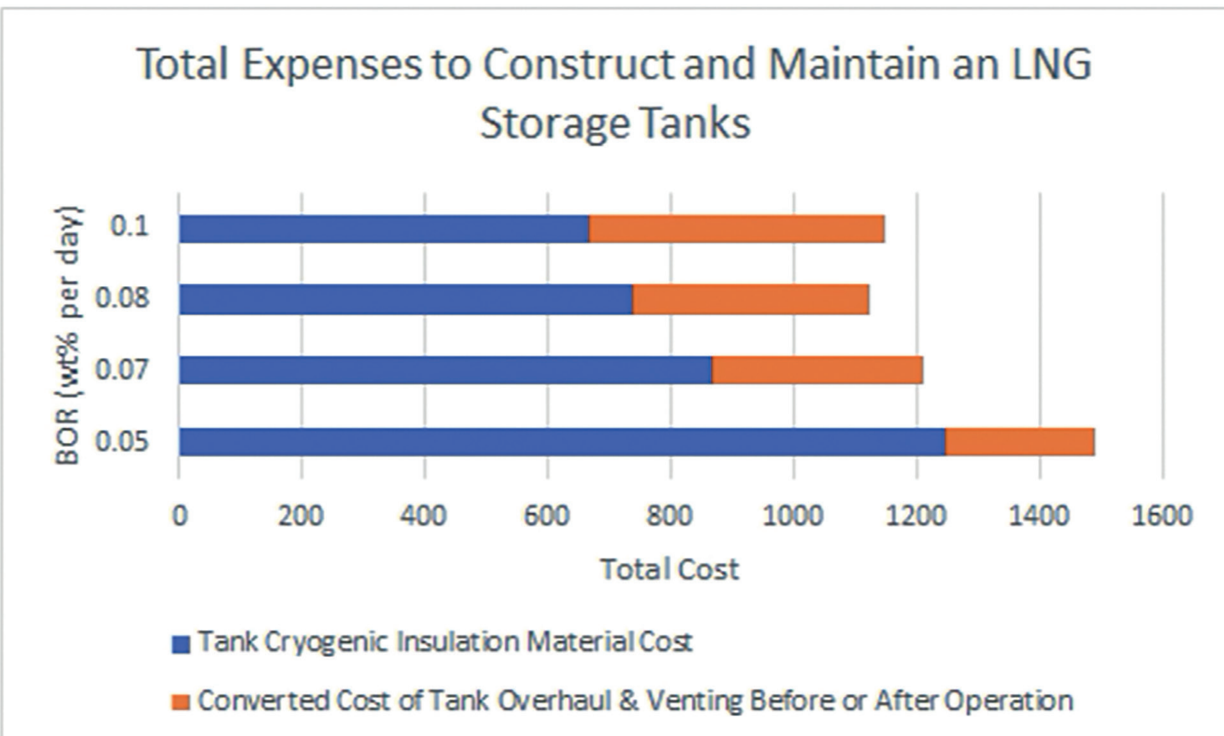


Figure 3: Cost of cryogenic insulation materials for LNG storage tank, the cost of operation and BOG ventilation, and total expenses for the entire operation (BOR is daily evaporation rate)[8].

To this end, a research group backed by the Natural Science Foundation of Hubei Province of China published a 2023 study that proposes a method to facilitate the removal of methane and nitrogen oxide emissions from LNGs[11]. Due to the low temperatures in the engine, the traditional method of using a methane oxidation catalyst (MOC) and an HN_3 selective catalytic reduction system (NH_3-SCR) would be too impractical and inefficient[11]. However, the study proposes a selective catalytic reduction system using CH_4 as a reducing agent instead (CH4-SCR), which is cheaper, smaller, and able to remove both CH_4 and NOx simultaneously. Although the low temperature of the LNG cooling process still slows the process, its effect will be mitigated with the introduction of non-thermal plasma (NTP) technology[11]. While NTP generation is held back by higher energy requirements, the study insists that it is integral to optimizing system energy consumption and efficiency.

However, the synergistic mechanism between NTP and catalysts remains unclear, limiting its optimization and development. Regardless, much research has been performed analyzing those synergistic mechanisms, developing synergistic catalysts for treatment, and optimizing energy consumption[11]. While such a technology is unattainable at the moment, the foundation is there to begin work on a proper implementation of this technology. With the research and progress this study reviews, the potential to create a CH_4 catalytic reduction system is achievable. If this method is constructed and properly tested, it could usher in a new age of clean LNG fuel, which operates at the same efficiency as conventional marine fuels without emitting GHGs.

Plastic Debris LNG Ships:

Furthermore, proposed developments have utilized LNG mechanisms to combat other forms of pollution in the ocean. Aside from transportation, the most severe epidemic in the marine industry is the ever-growing abundance of plastic debris (PD). The onset of industrialization in the 1950s drove many production lines, including an exponential growth in global plastic production[12]. However, over the past 70 years, plastic production continued to increase at a staggering rate, producing nearly 460 million tons globally in 2019[12]. Of that amount, an estimated 0.5% of that plastic is emptied into the ocean, meaning millions of tons of PD enter the sea at an annual rate[12]. This rate nearly constitutes an epidemic, not only for the ocean's ecosystem but for public safety as well.

As plastic is light and resistant to natural degradation, plastic particles tend to float on the surface, concentrating the water-resistant contaminants and polluting the surrounding seawater[13]. These plastics then break down into microplastics, which leave the seawater toxic and rife with millimeter-long plastic fragments[13]. This contaminated water then ends up in irrigation systems and is unknowingly ingested by humans, with analyses claiming that an average adult male consumes over 60,000 microplastics yearly[14]. With such a high source of pollution, global industries and organizations have initiated numerous plans to capture and recycle the millions of tons of PD in the ocean.

Cleaning ships with onboard facilities to dispose of waste have been deployed to collect and process debris buildups[15]. However, their efforts are limited by the debris' low packing density, which heavily impedes storage[16]. As a remedy, most cleaning ships implement a pulverizing and loading method, which converts processed plastics into uniform products to improve recyclability and portability. However, plastics are difficult to pulverize into smaller particles due to their low melting point[16]. This led to the development of a low-temperature pulverization (LTP) process to increase efficiency. Simultaneously, attempts were made to form a cooling system by utilizing the cold heat, also known as cold energy, from an LNG storage tank[16]. Taking inspiration from this attempt, a 2021 study from a research group based at the Pusan National University of Korea proposed a design of an LNG ship that uses the residual cold energy to fuel an integrated LTP system, proving the efficacy of LTP systems in PD processing and the efficiency of LNG-fueled ships as an approach to PD recycling[16].

Figure 4 indicates the layout of the main facilities within the vessel, and Figure 5 illustrates the proposed schematics for freezing PD for LTP. Ethylene glycol water (EGW) is used as the heat transfer medium due to its low freezing point. As the diagram indicates, LNG will lower the temperature of the EGW, and the circulating EGW combined with cold air blasts will decrease the temperature of the PD through exposure, causing it to freeze and become brittle.

From these schematics, the team constructed a prototype ship with the parameters and calculated the system's heat transfer rate in the pulverizer and mass flow rate of LNG, assuming an eight-hour workload per day for both. After many more calculations of LTP freezing capacities, the team initiated a practical test to determine the feasibility of the LTP process. The results of these tests proved successful, with PD loading capacities significantly expanded through LTP and compression alongside a dramatically reduced cost for refrigerants used in LTP. At the vessel's ideal speed, 2 tons of PD can be collected and 200 kg of PD can be processed in one hour, theoretically saving up to 253 kg of LN_2 per hour[16]. While there is room to improve energy conversion efficiency and other optimizations, the results from this test have effectively validated the use of LTP for fine particle production. With further refining, this LNG-fueled cleaning ship using an LTP system is an eco-friendly approach to the global marine pollution problem with the potential to advocate for the utilization of excess energy in other modern industries.

Conclusion:

To conclude, liquid natural gas is a promising answer to

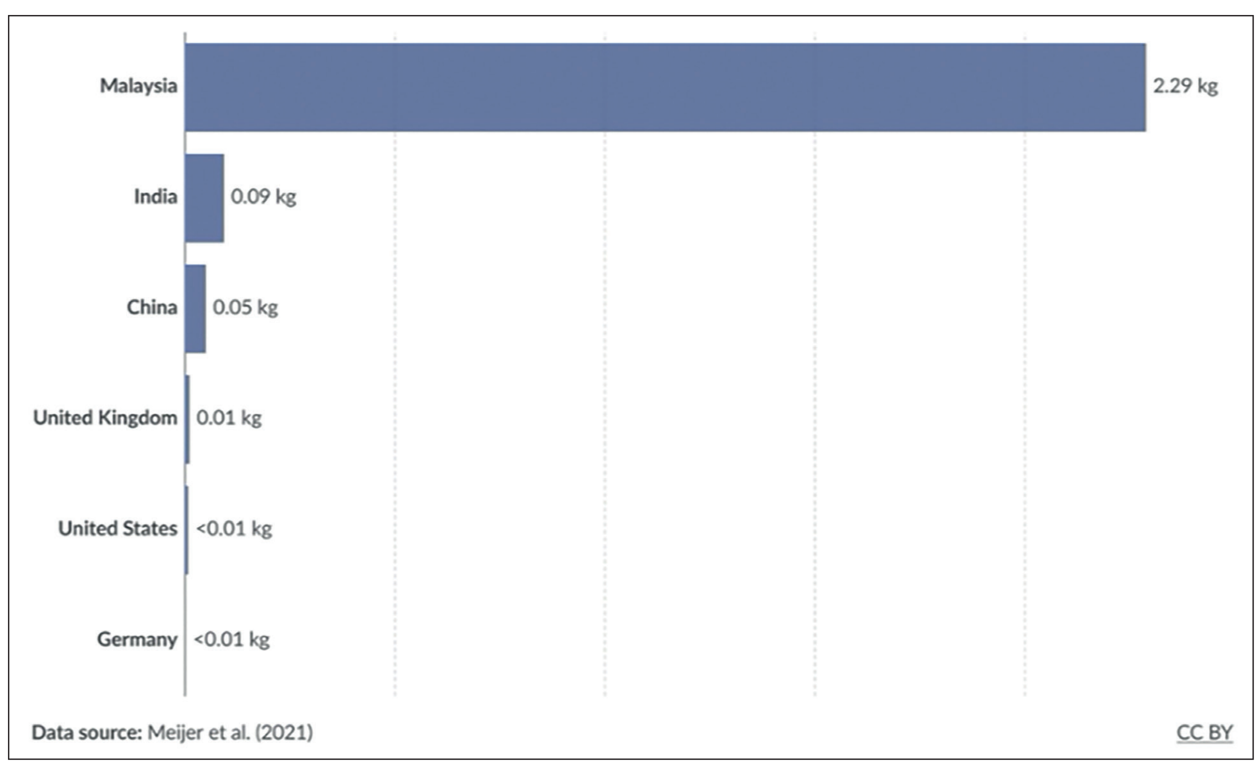


Figure 4: The estimated annual amount of plastic debris that entered the ocean per capita in 2019[12].

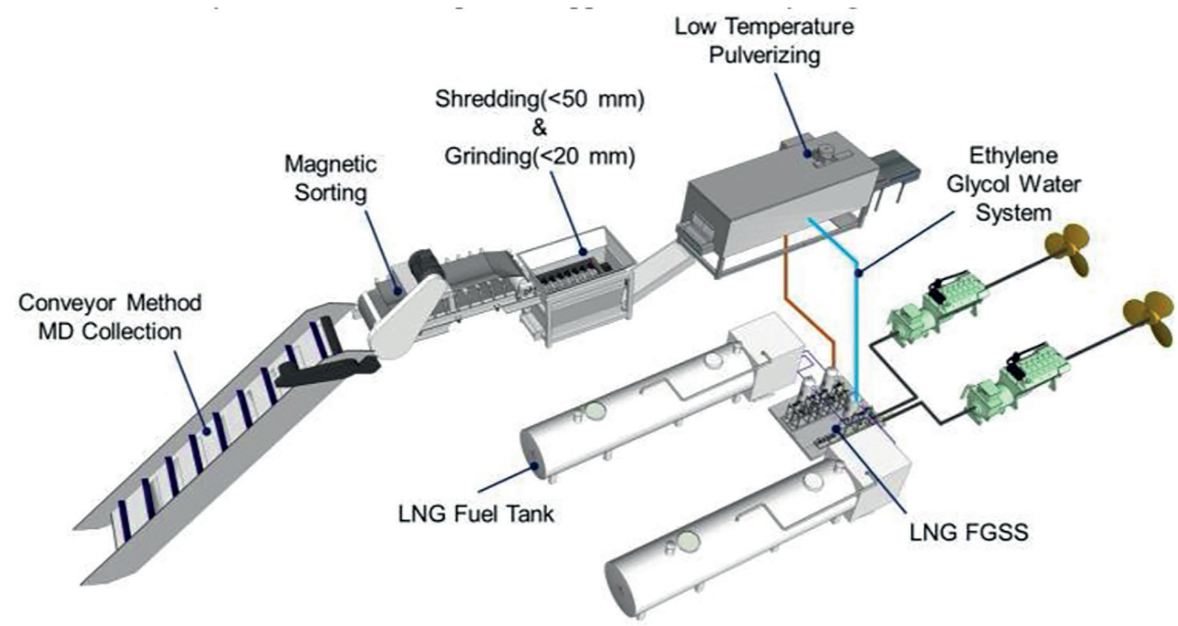


Figure 5: The layout for an LNG propulsion system equipped with an LTP system to catch the residual cold energy[16].

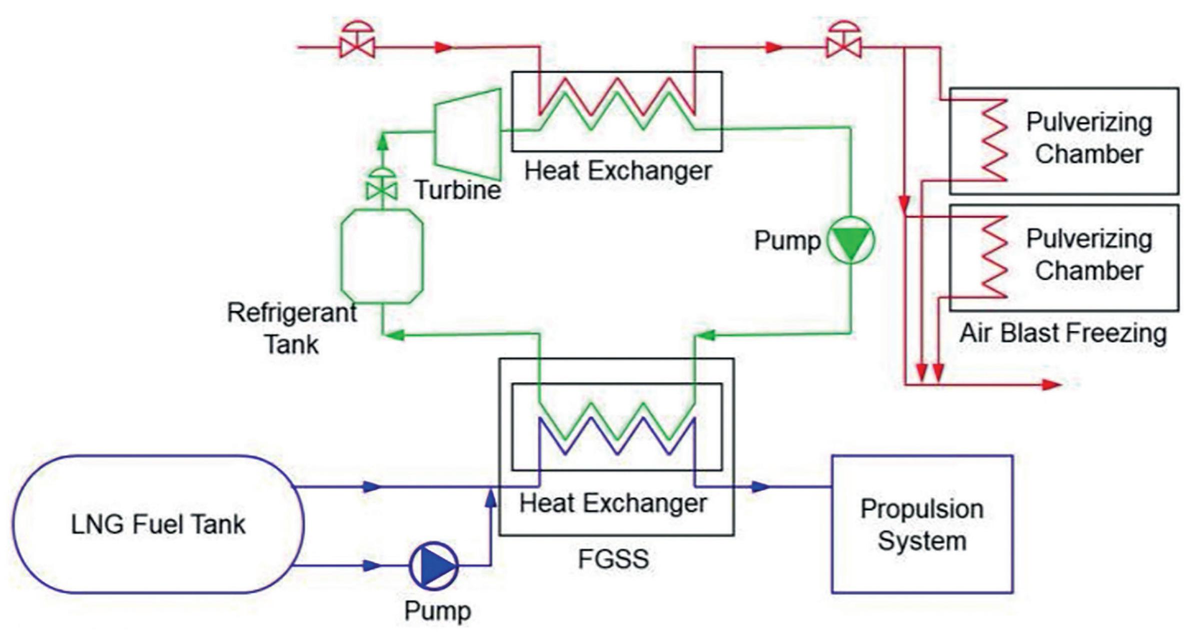


Figure 6: Schematic diagram of the proposed design. Contains the LNG propulsion mechanism (blue), the ethylene glycol water (EGW) system (green), and the pulverizing chamber with an air-blast freezing system (red)[16].

eco-friendly marine fuels and an ever-growing industry. Its many proposals and innovations call for an efficient fuel and a clean power source. From the onset of a standardized LNG storage tank system to a proposed catalytic reduction system that eliminates harmful greenhouse gases to a cleaning ship that uses the cold air generated by LNG in its pulverizing method, advancements in LNG and its applications all skew towards greater efficiency and fewer emissions. LNG development will inevitably continue in that direction until clean marine fuels become more efficient and more affordable than traditional fuels.

References:

1. Humphreys, Richard M. "Why Ports Matter for the Global Economy." WorldBank.org, 2023. [Online]. Available: https://blogs.worldbank.org/transport/why-ports-matter-global-economy
2. Wood, Nathan D., et al. "Maritime Transport: Fuels, Emissions and Sustainability." Marine Link, 2023. [Online]. Available: https://www.marinelink.com/news/maritime-transport-fuels-emissions-502716
3. Freight Waves. "How Many Gallons of Fuel Does a Container Ship Carry?" 2020. [Online]. Available: https://www.freightwaves.com/news/how-many-gallons-of-fuel-does-a-container-ship-carry/amp
4. Office of Energy Efficiency & Renewable Energy. "Sustainable Marine Fuels." [Online]. Available: https://www.energy.gov/eere/bioenergy/sustainable-marine-fuels
5. Livaniou, Styliani, and Georgios A. Papadopoulos. "Liquefied Natural Gas (LNG) as a Transitional Choice Replacing Marine Conventional Fuels (Heavy Fuel Oil/Marine Diesel Oil), towards the Era of Decarbonisation." Sustainability (Basel, Switzerland), Vol. 14, No. 24, 2022, pp. 16364-, https://doi.org/10.3390/su142416364. [Online]. Available: https://www.mdpi.com/2071-1050/14/24/16364
6. Office of Fossil Energy and Carbon Management. "Liquefied Natural Gas (LNG)" [Online]. Available: https://www.energy.gov/fecm/liquefied-natural-gas-lng
7. Peruško, Dalibor, et al. "Ageing of Liquified Natural Gas during Marine Transportation and Assessment of the Boil-Off Thermodynamic Properties." Journal of Marine Science and Engineering, Vol. 11, No. 10, 2023, pp. 1980-, https://doi.org/10.3390/jmse11101980. [Online]. Available: https://www.mdpi.com/2077-1312/11/10/1980
8. Fan, Yang, et al. "Optimal Design of Cryogenic Insulation System for Large Liquefied Natural Gas (LNG) Storage Tanks Based on Operation Factors." E3S Web of Conferences, Vol. 385, 2023, pp. 3010-, https://doi.org/10.1051/e3sconf/202338503010. [Online]. Available: https://www.e3s-conferences.org/articles/e3sconf/pdf/2023/22/e3sconf_isesce2023_03010.pdf
9. Pavlenko, Nikita, et al. "The Climate Implications of Using LNG as a Marine Fuel." International Council on Clean Transportation, 2020. [Online]. Available: https://theicct.org/publication/the-climate-implications-of-using-lng-as-a-marine-fuel/
10. Vuskovic, Bernard, et al. "Fostering Sustainable LNG Bunkering Operations: Development of Regulatory Framework." Sustainability (Basel, Switzerland), Vol. 15, No. 9, 2023, pp. 7358-, https://doi.org/10.3390/su15097358. [Online]. Available: https://www.mdpi.com/2071-1050/15/9/7358
11. Zhu, Neng, et al. "The Removal of CH[Sub.4] and NOIx/I from Marine LNG Engine Exhaust by NTP Combined with Catalyst: A Review." Materials, Vol. 16, No. 14, 2023, https://doi.org/10.3390/ma16144969. [Online]. Available: https://www.mdpi.com/1996-1944/16/14/4969
12. Ritchie, Hannah, et al. "Plastic Pollution." Our World in Data, 2019. [Online]. Available: https://ourworldindata.org/plastic-pollution
13. Thevenon, Florian, et al. "Plastic Debris in the Ocean: the Characterization of Marine Plastics and Their Environmental Impacts, Situation Analysis Report." Gland Switz. IUCN. 2015; 52:1–48. [Online]. Available: https://portals.iucn.org/library/sites/library/files/documents/2014-067.pdf
14. Cox KD, et al. "Human Consumption of Microplastics." Envir. Sci. Technol. 2019; 53:7068–7074. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.est.9b01517
15. 4Ocean. "UPDATE: The 4ocean Ocean Plastic Recovery Vessel." 2019. [Online]. Available: https://www.4ocean.com/blogs/operational-updates/update-the-4ocean-opr-vessel
16. Lee, Dong-Ha, et al. "Proposing a New Solution for Marine Debris by Utilizing On-Board Low-Temperature Eco-Friendly Pulverization System." Scientific Reports, vol. 11, no. 1, 2021, pp. 24364–13, https://doi.org/10.1038/s41598-021-03757-z. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8692423/#CR20

About the Authors

Dr. Raj Shah serves in the role of Director at Koehler Instrument Company in New York, boasting an impressive 28-year tenure with the organization. Recognized as a Fellow by eminent organizations such as IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute, and The Royal Society of Chemistry, he stands as a distinguished recipient of the ASTM Eagle award. Dr. Shah, a luminary in the field, recently coedited the highly acclaimed "Fuels and Lubricants Handbook," a bestseller that unravels industry insights. Explore the intricacies at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY).

His academic journey includes a doctorate in Chemical Engineering from The Pennsylvania State University, complemented by the title of Fellow from The Chartered Management Institute, London. Dr. Shah holds the esteemed status of a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute, and a Chartered Engineer with the Engineering Council, UK. Recently honored as "Eminent Engineer" by Tau Beta Pi, the largest engineering society in the USA, Dr. Shah serves on the Advisory Board of Directors at Farmingdale University (Mechanical Technology), Auburn University (Tribology), SUNY Farmingdale (Engineering Management), and the State University of NY, Stony Brook (Chemical Engineering/Material Science and Engineering).

In tandem with his role as an Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Dr. Shah's impact spans over three decades in the energy industry, with a prolific portfolio of over 625 publications.

Dive deeper into Dr. Raj Shah's journey at https://bit.ly/3QvfaLX.
For further correspondence, reach out to Dr. Shah at rshah@koehlerinstrument.com.

Dr. Vikram Mittal, is an Associate Professor at the United States Military Academy in the Department of Systems Engineering. He holds a PhD in Mechanical Engineering from MIT, an MS in Engineering Sciences from Oxford, and a BS in Aeronautics from Caltech. Dr. Mittal is also a combat veteran and a major in the U.S. Army Reserve. Previously, he was a senior mechanical engineer at the Charles Stark Draper Laboratory. His current research interests include various energy technologies, system design, model-based systems engineering and modern engine technologies. He has numerous publications in various peer reviewed journals.


Vikram Mittal

Simultaneously, within the dynamic internship program at Koehler Instrument Company in Holtsville, **Mr. Beau Eng** and **Mr. Gavin Thomas** are 2 standout participants. They are students of Chemical Engineering at Stony Brook University, Long Island, NY, where Dr's Shah and Mittal are part of the External Advisory Board of Directors at the university.


Beau Eng


Gavin Thomas

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA • Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com