Fuel Flexibility with GE Marine Gas Turbines

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With ever-tightening regulations on sulfur content in fuel and pressure to reduce emissions of other pollutants, LNG is gaining interest for marine propulsion applications. Long used as a fuel on land-based gas turbines, LNG offers low emissions and is the best fuel for the gas turbine in terms of performance and durability. However, what about using other fuels such as Liquid Petroleum Gas (LPG) or ethane for maritime propulsion? Is technology available today to allow ship owners to switch to burning hydrogen? GE's marine gas turbines burn alternative fuels employing the same technology that has been used in the power generation and oil and gas sectors for decades. These other industries have used various gas fuels–from pipeline quality methane which is very similar to LNG–to process exhaust gases that have low methane content but are high in hydrogen. This paper presents several case studies that illustrate how GE marine gas turbines can use a wide variety of gas fuels. Also explored will be the impact of different pollutants on engine performance and emissions.

Fuel Properties

A key aspect in evaluating any gas as a fuel is the make-up or constituents of the gas. There is no single mixture that describes a gas make-up. In fact, the constituents of LNG will vary worldwide as illustrated in Table 1, which shows the typical composition of LNG by country.

TABLE 1

Typical Composition of LNG Imports by Country

Origin	Methane (C1) %	Ethane (C2) %	Propane (C3) %	Butane (C4+) %	Nitrogen (N2) %
Algeria	87.6	9.0	2.2	0.6	0.6
Australia	89.3	7.1	2.5	1.0	0.1
Malaysia	89.8	5.2	3.3	1.4	0.3
Nigeria	91.6	4.6	2.4	1.3	0.1
Oman	87.7	7.5	3.0	1.6	0.2
Qatar	89.9	6.0	2.2	1.5	0.4
Trinidad & Tobago	96.9	2.7	0.3	0.1	0

Source: Groupe International Des Importateurs De Gaz Natural Liquéfié

Note that that range of just the methane varies by over 10% and the ethane by 70%. Diesel engine technology uses the methane number to provide an indication of the knock tendency of a fuel. It is the sum of the product of the proportion of constituent gases and their applicable knock resistance (for example, methane has a knock resistance of 100 while hydrogen has a value of 0). Understanding the knock resistance is important for engine performance. For example, the methane number of the Algeria gas is ~73 and the Trinidad and Tobago gas is ~90.

Gas turbine technology uses Modified Wobbe Index (MWI) as the main indicator of fuel gas composition.

$$\text{Modified Wobbe Index} = \frac{LHV}{\sqrt{SGgas \times T}}$$

This is equivalent to:

$$\text{Modified Wobbe Index} = \frac{LHV}{\sqrt{\frac{MWgas}{28.96} \times T}}$$

Where:

- LHV = Lower Heating Value of the Gas Fuel (Btu/scf)
- SGgas = Specific Gravity of the Gas Fuel relative to Air
- MWgas = Molecular Weight of the Gas Fuel
- T = Absolute Temperature of the Gas Fuel (Rankine)
- 28.96 = Molecular Weight of Dry Air

The MWI can be used to describe all gas fuels. Figure 1 shows the spectrum of gasses and compares the MWI and the gas heating value.

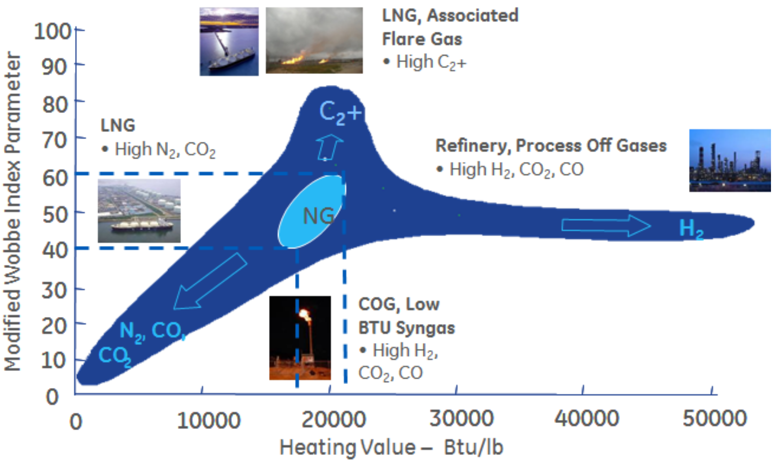

Figure 1 – Range of Gas Fuel Properties

The left portion of Figure 1 shows those gas fuels that have high levels of inert gasses that are typically generated from synthetic gas, such as gas released from landfills. In the center portion are the more typical gases; those from wellheads and some processed gases. Finally, the right portion of the graph represents the gases that can be burned from industry processes, such as coke oven gas, and flare gas.

As indicated by the blue dashed lines, a standard range of MWI is from 40 to 60. However as shown in Figure 2, GE marine gas turbines have demonstrated operation burning a wide variety of gas fuels.

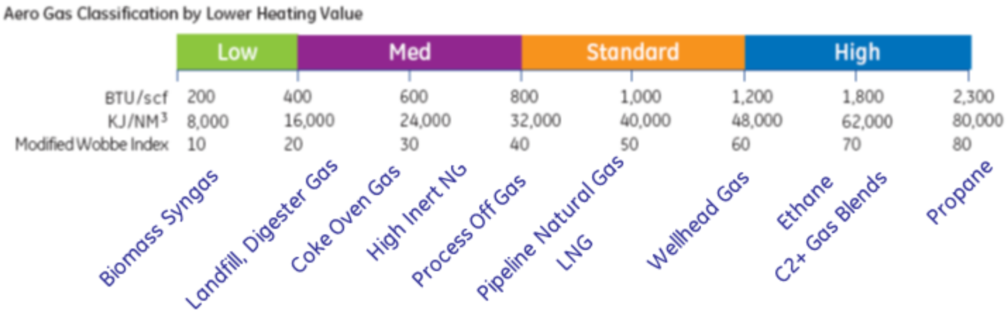

Figure 2 – Description of Gas Fuels used in GE Gas Turbines

The remainder of this paper will provide examples of different fuels across this spectrum and provide some insight on how these fuels impact gas turbine performance and emissions.

LNG

LNG is the easiest fuel for a gas turbine to accommodate. LNG production requires very tight control of the feed gas. Some fuel constituents which normally occur in pipeline-quality natural gas, like CO and CO2, are stripped prior to the liquefaction process. Figure 3 shows a comparison of the gas composition from a typical pipeline versus LNG.

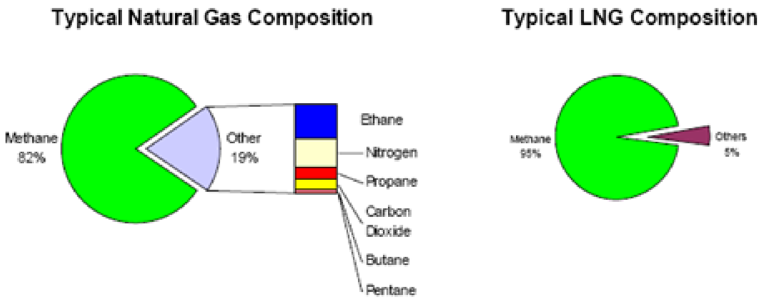

Figure 3 – Pipeline Natural Gas vs. LNG

Note the methane content for LNG is much higher and the "other" category is lower. Table 1 showed that there is still variation worldwide, however, compared to the gases listed in Figure 2, the variation in worldwide LNG supply does not significantly affect the performance of the gas turbine. On LNG carrier applications, variation of gas properties of the Boil Off Gas (BOG) have been noted during the voyage. During the beginning of a laden voyage, the BOG contains excess nitrogen, while at the end of the ballast voyage the remaining LNG will have an increased content of higher hydrocarbons such as ethane and propane. This variation has led to requirements to provide diesel engine controllers with information about the changing gas composition. For gas turbines, this variation during the voyage is insignificant; no special measuring equipment or modified control algorithms are required.

The gas turbine does not have any operating restriction when running on LNG; the engine can be started on LNG and accelerated to full load. There is no requirement for a pilot fuel. This has been demonstrated on over 3,150 aeroderivative gas turbines worldwide accumulating more than 110 million operating hours using natural gas. In addition, fuel switchovers from gas to liquid and back are automatically sequenced, not requiring any operator intervention. Time to complete a fuel switchover is under 30 seconds with no loss in power.

Key pollutants are significantly reduced when using LNG instead of MGO. CO2 emissions drop by over 30% and NOx emissions drop by 70%, making it easier to meet the 2.0 g/kWhr Tier III requirements. By using GE's proven Dry Low Emissions technology, its gas turbine can meet NOx levels below 0.3 g/kW-hr, which is well below the Tier III levels. When using LNG, gas turbines maintain "unmeasurable" levels of unburned hydrocarbons, or "methane slip."

LPG and Propane

LPG is sometimes used to describe propane fuel. However, LPG has many different variations in composition from source to source. Propane composition can vary from 20% up to 100% based on the source of LPG. One description of "commercial grade" propane would have similar components as shown in Figure 4:

COMPONENT	SPEC CONTENT	ANALYSIS
Propane	90.0 volume % min.	92.5%
Butane and heavier	2.5 Liquid volume % max.	2.5%
Propylene	5.0 Liquid volume % max.	5.0%

Figure 4 – Composition of HD5 Propane

This yields a propane fuel with a specific gravity of 1.53 and LHV of 46,364 kJ/kg.

When evaluating propane versus LNG, there are three key factors to consider:

1. It is recommended to maintain the fuel temperature of the delivered propane at ~149°C. This helps reduce the MWI and keeps the propane in a single phase. By reducing the MWI, the operating range of the gas turbine expands without making major modifications. For the LM2500 family of gas turbines, a minor change to the fuel nozzle tip area is done to enable starting and full power operation on propane with this temperature. Two phase flow or a phase change occurring within the gas turbine's fuel system must be avoided (see Figure 5). Commercial grade propane contains some amounts of other hydrocarbons and heavier molecules. These components will impact the dew point of the blended gas. A temperature higher than that required for LNG is needed to avoid any liquids being injected into the combustor.

2. Combustion of propane will have a significantly higher flame temperature as compared to combustion with natural gas. Higher combustor flame temperatures will generate higher levels of NOx. Propane will generate close to 60% higher NOx as compared to LNG. This is similar to the NOx levels obtained when using a refined diesel fuel. GE gas turbines can meet the Tier III limits with propane fuel.

3. Finally, the specific gravity of this fuel is greater than 1; this gas is heavier than air. Careful consideration must be given to all safety systems. Inside the gas turbine enclosure, fire detectors must be selected and arranged to account for propane. Additionally, the gas turbine enclosure ventilation strategy will require an update to assure proper purging of the lowest elevations. The ship's general arrangement strategy will also need to assess any potential vent points of propane and resulting hazards.

   Given the proper attention to details, GE marine gas turbines can be operated with commercial grade propane defined as HD5 propane.

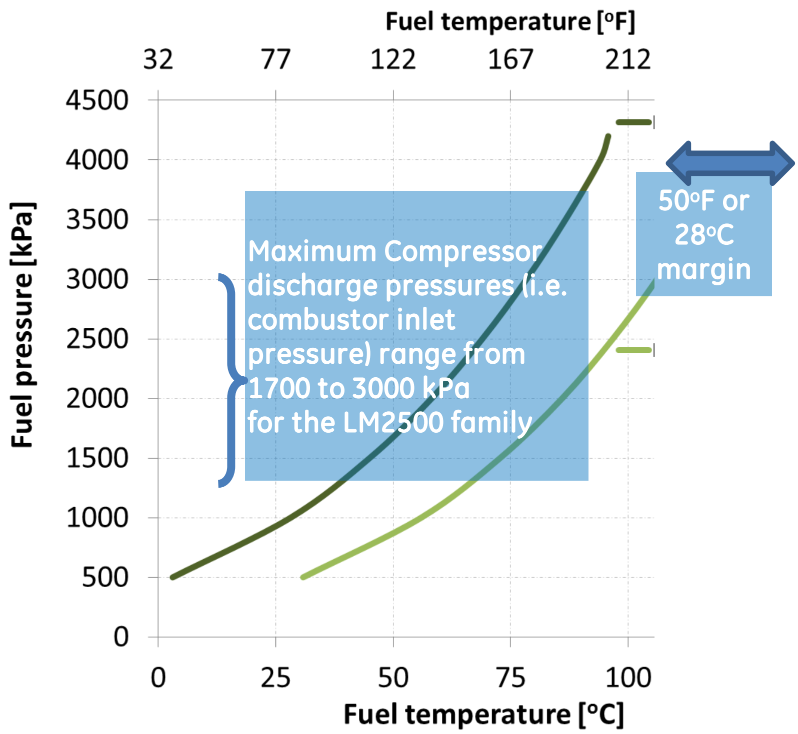

Figure 5 – Vapor Pressure Curve for Commercial Grade Propane

Ethane

GE's aeroderivative gas turbines have experience operating in a variety of applications requiring a wide range of fuels, including up to 100% propane. Experience gained from these units demonstrate the viability of using ethane as the primary fuel.

Similar to LNG, there is not one uniform mixture for ethane. However, the variation is less than LPG; a typical ethane position is shown in Figure 6.

COMPONENT	SPEC CONTENT	ANALYSIS
Ethane	95.0 Liquid volume% min.	95%
Methane	3.0 Liquid volume % max.	0.5%
Ethylene	1.0 Liquid volume % max.	1.0%
Propane and Heavier	3.5 Liquid volume % max.	3.5%

Figure 6 – Composition of Ethane

This results in a specific gravity of 1.05 and a LHV of 47,515 kJ/kg. Note the similar LHV with propane, ~2.5% delta. Like propane, fuel heating is used to maintain the MWI and keep the fuel in single phase. Ethane also will generate higher flame temperatures, similar to propane. The heavier specific gravity will also require the same safety changes with respect to LNG as propane.

Overall, propane and ethane have very similar characteristics and impacts when used with a GE marine gas turbine.

Hydrogen

Pure hydrogen as a fuel for a gas turbine has not yet been developed. Other applications which contain high concentrations of hydrogen are coke oven gas, blast furnace gas blends, and other industry process waste gases. Figure 7 shows a sampling of GE's high hydrogen gas experience.

Figure 7 – GE Gas Turbines with High Hydrogen Fuel Content

In these applications, the hydrogen content is the result of another process, for example a coke oven burning bituminous coal to make steel. The exhaust gas stream of the coke oven has a low overall MWI of ~30 due to the presence of about 20% (volume) inert gases. Hydrogen makes up the largest component with ~65%.

Burning any significant concentration of hydrogen in a gas turbine has some serious design challenges. The specific gravity for hydrogen is 0.0696, about 7% of the density of air. The molecules of hydrogen are smaller than all other gases, and these can diffuse through many materials considered to be airtight. This makes the fuel transfer piping design for hydrogen challenging. Hydrogen gas forms explosive mixtures with air in concentrations from 4% to 74%. The auto-ignition temperature of hydrogen in air is 500°C. This drives complexity in starting strategies and back-up fuels when using hydrogen.

Design changes needed to use a hydrogen mixture include the following:

- Start and low power operation on alternate fuels
- Pure inert gas (usually nitrogen) for fuel supply pipe purging
- Gas turbine enclosure fire detection system optimized for hydrogen leaks
- Class III certified electrical equipment

As compared to propane and ethane, hydrogen will have a higher NOx emissions. The projects shown in Figure 7 are capable of meeting Tier III NOx regulations. However at this time, GE has not evaluated NOx levels when burning pure hydrogen.

Even with these challenges, GE marine gas turbines have design capabilities to accommodate up to 85% hydrogen.

Case Study – Natural Gas and LNG as a Fuel

GE gas turbines have used natural gas as a fuel for over 45 years. Applications range from driving natural gas pipeline and LNG liquefaction compressors to power plants and offshore oil and gas platforms. As Figure 3 indicates, the variation in LNG composition is much less than observed in typical natural gas.

One example is the ConocoPhillips LNG plant in Darwin, Australia shown in Figure 8; this facility has been operating since 2006.

Figure 8 – ConocoPhillips Darwin LNG Facility

The Darwin LNG facility uses six GE LM2500+G4 gas turbines to produce 3.7 million tonnes of LNG per year. ConocoPhillips selected the Optimized Cascade[SM] LNG process which relies on two gas turbine compressor trains for each of the gas refrigeration steps (see Figure 9 for a schematic of this process).

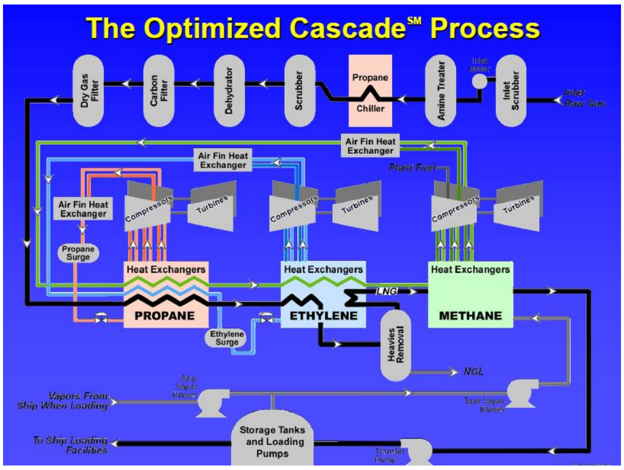

Figure 9 – ConocoPhillips Optimized Cascade LNG Process

The initial feed gas for Darwin falls within the variation observed for natural gas; methane content of at least 80% with the remaining composition a mixture of a small amount of ethane and inert gasses. Typical MWI ranges are from 47 to 53.

The fast ferry *Francisco,* owned by Buquebus and built by Incat, began operation in 2013 fueled by LNG (see Figures 10 and 11).

Here, LNG is stored in two 40 cubic-meter tanks, sized to make the roundtrip from Buenos Aires to Montevideo. The LNG is pumped to required pressure in liquid form, and the gas turbine exhaust heat then vaporizes the LNG. Current regulations require that *Francisco* operate on diesel fuel when in port. Once *Francisco* clears the harbor area, it switches to running on LNG while accelerating to the target ship speed.

Figure 10 – LNG Powered *Francisco* ferry

Figure 11 – *Francisco* Design Details

Case Study – Propane as a Fuel

A GE LM6000PC engine in Japan has over three years of operating experience running on propane. The gas turbine's fuel nozzles were configured to run on either natural gas or propane. To accommodate propane, the fuel delivery system and gas turbine enclosure required the following changes:

- High temperature material for fuel metering valves and shut-off valves
- Increased enclosure ventilation system capability
- Updated fire protection system calibrated to detect propane leaks
- Heat tracing and insulation of propane fuel supply lines
- Updated starting strategy

This customer elected to use kerosene for starting and switched to propane at 15 MW. However, the fuel system design provided capability to start on propane. Performance and operability were the same as natural gas.

In addition, GE has been working with Hyun-Seong Marine Cruise Transport (HS MCT) and its partners to develop a propane fueled ferry (see Figures 12 and 13 for sketches of the proposed ferry).

Figure 12 – HS MCT Propane Fueled Ferry

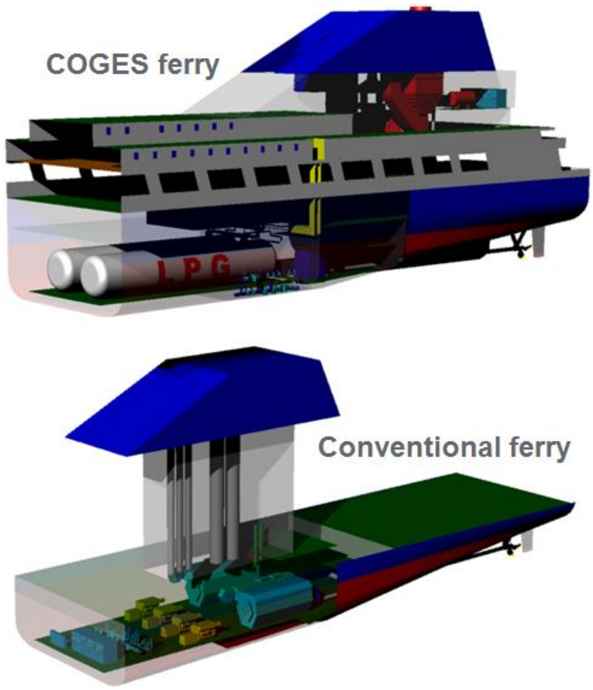

Figure 13 – COGES Powered Ferry Comparison

The HS MCT ferry will employ GE's COmbined Gas turbine Electric and Steam (COGES) solution using propane as the primary fuel. The compact gas turbine solution will allow HS MCT to use more ship space for generating revenue.

The ferry design will use two type C propane tanks which will provide capability for the proposed roundtrip journey. The ship will be able to start and operate over the entire speed range on propane. Switching to back-up diesel will be automatically sequenced and completed in about 25 seconds if needed. Bureau Veritas completed their assessment and issued their Approval in Principal in August 2017.

Case Study – Hydrogen Mixture as a Fuel

As noted previously, there are no current gas turbines use pure hydrogen as a fuel. One example of a high hydrogen content of a gas mixture is a GE's LM2500+G4 engine that burns coke oven waste gas as a fuel. Figure 14 shows a schematic of the coke oven gas site in Henan, China, which has been in operation since 2012.

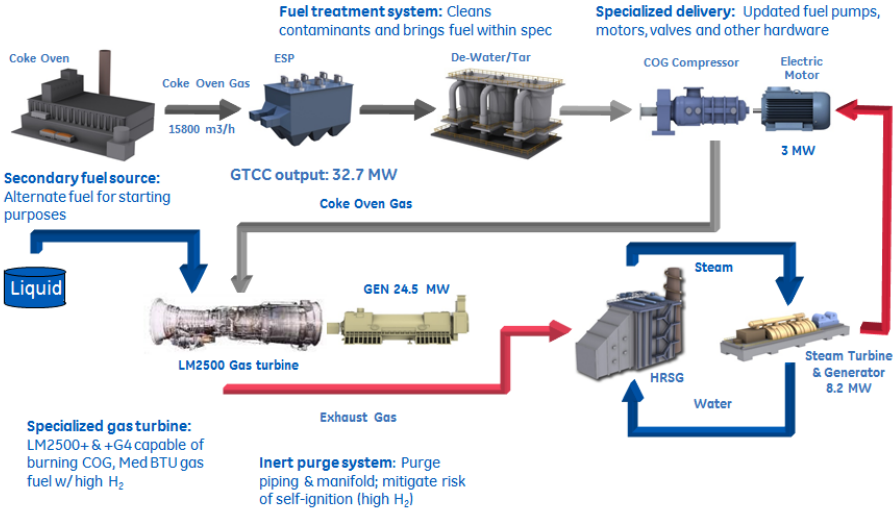

Figure 14 – Henan Steel Coke Oven Gas Fueled Site

Coke oven waste gas from the Henan steel mill is first sent to a fuel treatment system. Here, gas contaminants–especially tar balls–are removed from the gas. The gas is then sent through a gas compressor to deliver it at the required pressure. Changes to the standard gas turbine include modifications to the fuel delivery system to accommodate the higher volume flows as well as the required changes for safe operation with hydrogen. This includes a purge system for the gas delivery system consisting of very pure nitrogen, to reduce any risk of autoignition of the hydrogen.

Conclusion

GE's gas turbines are used not only for marine propulsion solutions, but also for land-based power generation, driving gas compressors, and offshore oil and gas processes. These applications have used natural gas as a fuel for over 45 years, accumulating more than 110 million operating hours. Natural gas, LNG, propane, ethane, and some hydrogen blend of fuels all have been successfully demonstrated. As the marine industry looks for alternate solutions to reduce pollutant levels, GE marine gas turbines are proven to operate on these fuels and provide options for shipbuilders and owners to meet current and future regulations.

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