START YOUR ENGINES

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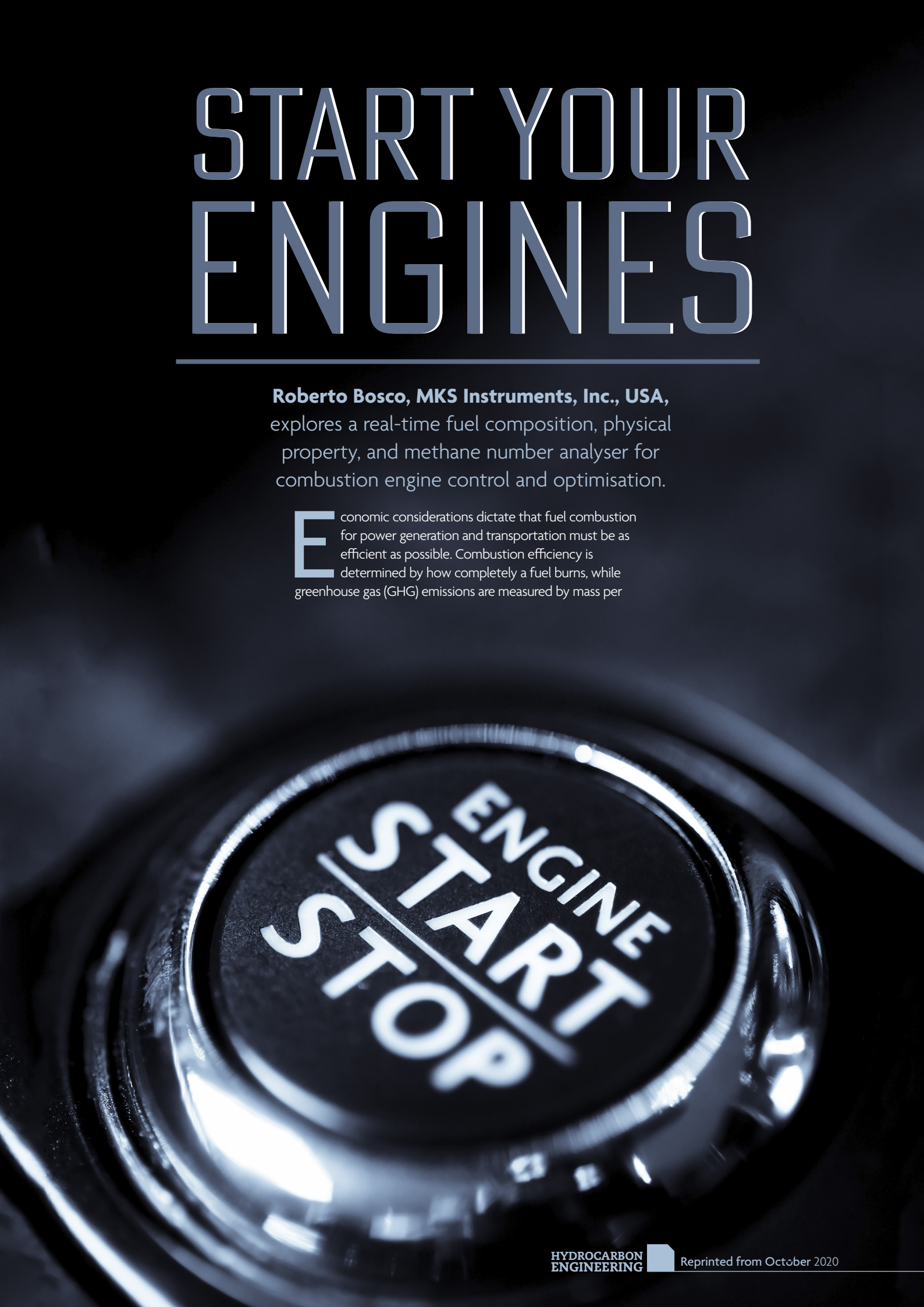
explores a real-time fuel composition, physical property, and methane number analyser for combustion engine control and optimisation.

Economic considerations dictate that fuel combustion for power generation and transportation must be as efficient as possible. Combustion efficiency is determined by how completely a fuel burns, while greenhouse gas (GHG) emissions are measured by mass per



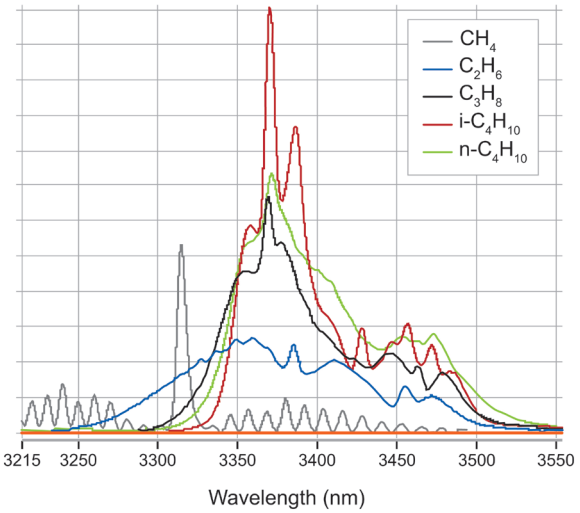


Figure 1. Infrared absorption spectra of C1 – C4 hydrocarbons.

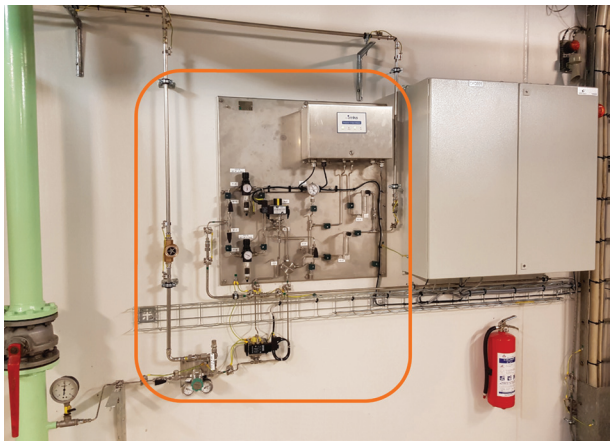


Figure 2. Precisive Gas Analyzer installation for online gas quality monitoring of the fuel feed to a natural gas-ICE used for electrical power generation.[9]

unit of energy produced. Stoichiometric combustion converts all the hydrocarbons to carbon dioxide and water, i.e.:

$$CH_4 + 2O_2 \text{---> } CO_2 + 2H_2O$$

Combustion efficiencies depend on the design of the combustor and on the fuel/oxidant ratios in the process; the optimal fuel/oxidant ratios for a fuel depend on its physical and chemical properties. Natural gas or LNG fuels have lower GHG emissions than oil or coal.[1] These and other factors have quadrupled the use of natural gas for energy production since 1985.[2] Natural gas is rapidly displacing coal-fired generation today and is expected to do so well into the future. LNG is finding ever-increasing use as a transportation fuel, especially as a low emission replacement for high sulfur fuel oil (HSFO) in marine applications that must meet IMO2020 regulations.

Natural gas and LNG as fuel

Natural gas and LNG fuels are mixtures of light hydrocarbons, typically C1 – C5 alkanes, CO_2, and nitrogen. The relative amounts of the gases in the fuel varies, depending on the source and changes that arise from differential boil-off during storage and transportation. Different compositions in natural gas and LNG produce different combustion characteristics. This is, in part, due to the fact that the energy density of the fuel is the sum of the recoverable energy from chemical combustion plus any energy recoverable by returning all reaction products to 25 °C or other standard temperatures (this is the higher heating value [HHV] of the fuel). For example, the HHV for methane is 55.5 MJ/kg. Other light alkane gases have different HHVs (ethane, C2 – 51.9 MJ/kg; propane, C3 – 50.35 MJ/kg; butanes, C4 – 49.50 MJ/kg; pentanes, C5 – 49 MJ/kg; etc.). The energy density of natural gas or LNG fuel depends, therefore, on the relative proportions of C1 to C5 hydrocarbons in the fuel.

Internal combustion engines for power generation must be tuned to the knock resistance of the fuel for safe and efficient operation. The methane number (MN) is used as a metric for the knock resistance of natural gas fuels. It is similar to the octane number used to indicate the quality of gasoline in that it measures the ability of the fuel to undergo compression before it ignites. Fuel/air mixtures that ignite at the wrong point in the ignition cycle produce engine knock. While mild engine knock may only increase pollutant emissions, severe knock can physically destroy an engine.[3] For this reason, engine manufacturers typically tune engines to the worst-case fuel scenario at the expense of engine performance.[3] The MN for natural gas fuels ranges between 60 to 100, while that for LNG ranges between 50 to 95.[4] Convenient MN calculators are available (based on the relative concentrations of C1 – C5 in the fuel) from Cummins, Wärtsilä, and DNV-GL.[5,6,7] The ability to determine the MN of a fuel in real-time is therefore highly desirable, since it would allow engines to accept a wider variety of natural gas and LNG fuels while still maintaining optimal engine performance.

Chemical speciation and composition analysis of natural gas

Historically, natural gas and LNG fuel gas speciation and composition analysis requirements have been met with gas chromatography (GC). GC separates and measures the components in natural gas using adsorption column separation techniques. GC measurements are not suitable for real-time fuel analysis since measurement times for a mixture are between 90 sec. and 5 min.

Infrared (IR) absorption spectroscopy is a more suitable technique for rapid real-time chemical composition measurements in natural gas and LNG applications. Most chemical compounds absorb characteristic wavelengths of IR radiation; IR spectroscopy measures the absorbance at signature IR wavelengths that are passed through a sample. The characteristic absorbance is related to the concentration of the compound by the Beer-Lambert Law:

$$log_{10}(I_0 / I) = elc$$

Where, I_0 is the incident IR intensity, I is the transmitted intensity, e is the molar extinction coefficient, l is the path

length through the sample, and *c* is the concentration of the compound of interest.

Equipment requirements are relatively simple and IR spectroscopy is fast – only seconds or sub-seconds are needed for a full analysis of the composition of a sample. IR spectroscopy is commonly used for chemical analysis in industrial processes ranging from combustion product analysis to beverage process monitoring.

The primary challenge to using IR spectroscopy in real-time natural gas and LNG analysis is the spectral overlap in the spectrum of the hydrocarbon mixtures in natural gas. While the absorption spectrum for each hydrocarbon is unique, that of a mixture suffers from severe peak overlap in the spectral region where concentration measurements are made (Figure 1), making quantitative analysis difficult.

This article will describe the analysis of natural gas fuels using the MKS Instruments Precisive® Gas Analyzer that employs a Tunable Filter Spectroscopy (TFS™) based IR analyser. It is specifically designed for the multi-component analysis of hydrocarbon gas mixtures in industrial processes.

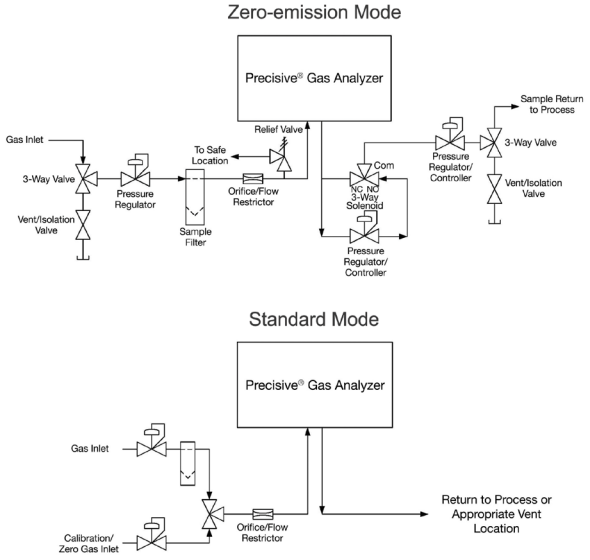


Figure 3. Conceptual gas line schematics for gas sampling systems used in standard and zero-emission mode methodologies.

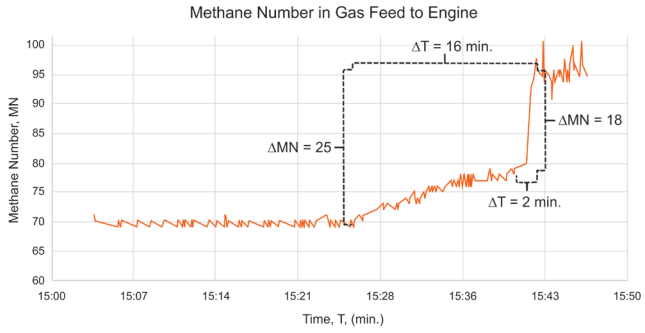


Figure 4. Online MN trace for the fuel feed to a natural gas turbine genset used for electrical power generation.[8]

A real-time monitor of fuel quality

The Precisive Analyzer performs real-time measurements of fuel gas composition, calorific content, and MN using a wavelength-sweeping tunable filter spectrometer for fast (down to one second) and accurate measurement of the composition of the fuel. It uses a chemometric pattern recognition algorithm that quantifies the C1 – C5 (and CO_2, if needed) concentrations in the fuel and compensates for non-linearities and other unwanted spectral behaviours that are unavoidable in real-world measurements.

IR absorbance is measured in a flow-through cell suitable for continuous monitoring. There is no need for carrier gas, fuel gases, or onsite calibration gases, significantly lowering operating costs. It is factory-calibrated and requires negligible maintenance. The chemometric algorithm produces accurate and robust speciated concentration values for C1 – C5 content in the fuel with simultaneous measurements of CO_2, carbon monoxide, hydrogen sulfide, nitrogen (balance), and other compounds. In addition, HHV, lower heating value (LHV), Wobbe index, and specific gravity of the fuel can be measured (based on ISO6976). Precisive Analyzers used for internal combustion engine (ICE) fuel monitoring and control are configured with multiple MN outputs based on Cummins, Wärtsila, and DNV-GL algorithms. The analyser can be installed in Division 2 and Zone 2 hazardous area classifications.

The Precisive Analyzers have been deployed in commercial gas monitoring applications for natural gas fuelled engines. Figure 2 shows an online gas quality monitoring installation that monitors the fuel quality for an approximately 6 MW natural gas-fuelled genset serving ~1000 customers.[8] In operation, a small flow of fuel gas (0.2 to 0.5 standard litre per minute) is sampled from the main fuel line and directed through the internal gas cell of the Precisive Analyzer, which determines the IR spectrum. Gas exiting the analyser can be vented to atmosphere or returned to the process when operated in a zero-emissions mode utilising MKS patented methodologies. Gas schematics for standard and zero-emission mode methodologies are shown in Figure 3. When operated in zero-emissions mode, zero gas cylinders are not necessary for routine operation, which reduces operating expenses. Relatively simple automation and control allows the analyser to perform continuous, online, and unattended analysis. Communication with the plant's distributed control system (DCS) is through MODBUS over TCP/IP or RS485.

Operational data

Figure 4 shows the variability in the MN of the gas from the local grid that was being monitored by the equipment shown in Figure 2. The gas quality of the engine fuel is seen to vary quickly, with large swings in gas quality possible over very short times. MN changes of nearly 20 units were observed in the fuel feed to the engine within a 2 min. window. Such changes are known to have a significant impact on the engine efficiencies. Recent studies have demonstrated that significant improvements in engine efficiencies can be realised when real-time, online fuel quality monitoring is combined with adaptive control algorithms that adjust the engine operating parameters to accommodate the rapid changes in the MN of incoming fuel.[8,9] Such combinations of

real-time fuel analysis with dynamic engine control permit the continuous optimisation of engine performance and the minimisation or avoidance of engine derating practices.

Fuel savings from real-time monitoring of natural gas fuels

As noted, real-time monitoring of the fuel quality enables dynamic tuning of an ICE, producing significant fuel savings. This is especially true for large internal combustion engines of 5 MW or more where a 5% increase in fuel efficiency can be realised. This means that, with ICE operational lifespans of 15 to 20 years, fuel cost savings of between US$1 million to US$7 million can be realised over the life of an engine. Installations with multiple natural gas engines, such as ICE power plants, will experience commensurately larger fuel cost savings.

Conclusion

Variations in the quality of natural gas fuel have a significant effect on the cost of electricity generated using this fuel. Variations in costs due to fuel quality arise primarily from the impact of fuel quality on engine operating efficiency and knock resistance. Effective real-time, online monitoring of the fuel quality, when combined with adaptive control of engine performance, can therefore realise significant savings in fuel costs for natural gas-fuelled electricity gensets. A hydrocarbon gas analyser that employs TFS-based IR spectroscopy has been demonstrated to be effective in providing real-time data on fuel composition and quality for this application. Installation of this type of fuel quality monitoring, when combined with adaptive control of the engine, can produce fuel cost savings of as much as US$7 million over the lifespan of a typical engine used in electrical power generation.

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