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EXPANDED FUEL TEST CAPABILITIES FOR GE AERODERIVATIVE GAS TURBINES

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ABSTRACT

Oil & Gas and industrial gas turbine end users are increasingly searching for lower cost fuel alternatives to reduce their largest operating expense. In the LNG world, plant profitability is maximized when gas turbines are capable of burning fuel streams that can have elevated levels of inert or heavier hydrocarbon content and exhibit high variation in composition over short periods of time. Premixed combustion gas turbines are particularly challenged by fuel variability.

Over the last 5 years, GE has launched engineering programs for its Aeroderivative Gas Turbines to expand testing and gas turbine capabilities by investing over $5MM to develop its fuel flex test facility for LM2500, LM6000 and LMS100 series gas turbines.

This paper will review the fuel capabilities of Distributed Power's Houston depot test facility and results of full-scale LM2500+G4 DLE gas turbine testing executed in 2013. The testing consisted of mixing the normal pipeline natural gas supplied to the test facility with various levels of nitrogen to demonstrate NOx and CO emissions as a function of nitrogen mole fraction, starting and load change capabilities at the lowest achieved calorific value entitlement level, and advanced fuel properties rate of change thresholds from minimum to full load.

INTRODUCTION

Aeroderivative gas turbines have a proven track record of efficient and reliable operation on pipeline quality natural gas fuel, backed up by millions of operating hours. Export quality, regasified LNG is a premium quality fuel for Aeroderivative gas turbine due to the "purifying" nature of the LNG production process.

During gas liquefaction process, the majority of hydrocarbon compounds heavier than methane are removed from the feed gas. Inert compounds such as nitrogen and carbon dioxide are also removed from the main stream of the gas to be liquefied.

Gas turbines employed in LNG plants either as mechanical drivers or for power generation, usually burn the lowest-cost fuel gas streams. Over the past decade, GE has seen a noticeable and growing demand for gas turbines with dry low emission (DLE) combustion systems to have the additional capability to respond to fast changes in gas composition and properties without tripping off line or deviating from the demanded power. Such fast changes may occur in the liquefaction plant during production upsets, for example when a nitrogen rejection unit goes offline. In such case, the amount of nitrogen in the fuel gas will change dramatically in a matter of minutes or even seconds.

Switching between gases from the different sections of the LNG process can present equivalent operability challenges for any gas turbine. Such capability of the premixed gas turbine combustion system to maintain the stable load independently of dynamic fuel property changes will be of great advantage for LNG gas operators, in terms of both operational flexibility and profitability from utilizing a by-product high-inert / higher order hydrocarbon fuel streams.

In certain regions, there also other sources of fuel variation coming into play. In Europe, new sources of natural gas have become available due to increased imports from diverse exporters, wider and more frequent introduction of re-gasified LNG into gas transmission and distribution pipelines. Moreover, the European Union is in the process of implementing a harmonization of European gas quality standards that may allow range of gases different than many national gas grid codes (IGU, 2011; Bowers, 2012). As a result, constant gas composition at any given location in EU gas pipelines cannot be guaranteed, although to date the variation observed has not been as rapid as in LNG plant applications.

NOMENCLATURE

C2+ – Natural Gas hydrocarbon components heavier than methane
CO_2 – Carbon Dioxide
DLE – Dry Low Emissions
GC – Gas Chromatograph
HHV – Higher Heating Value, MJ/Nm^3
LHV – Lower Heating Value, BTU/scf
LNG – Liquefied Natural Gas
MWI – Modified Wobbe Index based on LHV, SG and temperature, $BTU/(SCF*°R)^{0.5}$
N_2 – Nitrogen
NG – Natural Gas
PLC – Programmable Logic Controller
ROC – Rate of Change (of fuel properties)
SG – Specific Gravity
T48 – Temperature at power turbine inlet
WI – Wobbe Index based on HHV and SG, MJ/Nm^3
WIM – Wobbe Index Meter

IMPACT OF GAS VARIABILITY TO PREMIXED COMBUSTION SYSTEMS

When dry low emission (DLE) aeroderivative gas turbines first were introduced some 16 to 18 years ago, they typically were operated with “standard” fuel gases with a stable set of properties, i.e. pipeline quality natural gas, year round. From the beginning, GE’s aeroderivative gas turbines have been designed to burn fuels with a broad range of MWI, historically stated by GE (GE Energy, 2009) as 40-60 (MWI based on LHV and SG, $BTU/(SCF*°R)^{0.5}$ and equivalent to HHV-based WI of 37.3-56 MJ/Nm^3 at 15 °C) and more recently expanded to 36-60 (HHV-based WI of 33.6-56 MJ/Nm^3 at 15 °C). This capability has been demonstrated with more than 900 DLE gas turbine installations with various and stable MWI fuels within the given range.

DLE gas turbine combustors are normally “mapped” during commissioning, when replaced in the field, and periodically thereafter. Mapping is a process of tuning the fuel control settings to advanced combustor operability (low dynamic pressure) and obtaining NOx/CO exhaust emissions below regulatory limits with a single fuel composition. Historically, the expectation was that the gas fuel properties would remain within 1 percentage point of the initial MWI during steady-state operation or 3 percent during transient fuel changes. Today, however, several end users have experienced or are anticipated to have either a change in gas fuel properties to a significantly different MWI or a periodic MWI amplitude variation greater than 3 percentage points, with change occasionally occurring at a rapid rate.

A change in the gas fuel to a significantly different set of gas properties that are expected to remain in effect for long periods of time is typically accommodated by re-mapping the combustor. When significant changes in gas properties have occurred on a regular or semi-regular basis, either rapidly and/or greater than 3 percent in magnitude within the 36-60 MWI range, several operators have reported gas turbine operability issues and/or emissions exceedances. These operability issues are the result of high combustor dynamic pressures (acoustics) resulting in loss of power, and/or difficulty in maintaining stable power within the capability of gas turbine control to lower acoustics, with the most severe being either a step to idle, combustor flameout or a trip. In addition, existing gas turbine control logic or user intervention to abate acoustics by adjustment of fuel flow distribution between combustion zones may result in further exceeding the emissions limits.

Testing various gas compositions permits the exploration and validation of fuel nozzle or premixer, as well as the overall combustor design entitlements in terms of NOx/CO emissions and operability boundaries. For example, depending on the specifics of the fuel composition, the flame temperature design space boundaries between incipient lean blowout and high acoustic onset will shift from a standard fuel in both level and magnitude. The test platform described below elicits useful data upon which to make decisions to eliminate excessive overlaps in design and fuel system flow and pressure limits. In addition, it demonstrates emissions and operability with gas blends representative of going beyond the extremes, where possible, with respect to customer gas fuels.

TEST FACILITY AND INSTRUMENTATION

Gas mixing system description

A suitable test platform and large-scale industrial gas blending system were required to quantify gas turbine operability, starting, load ramp-up and ramp-down, and MWI rate of change handling capabilities to further advance fuel flexibility for GE’s aeroderivative gas turbines. This includes the LM2500, LM6000 and LMS100 product lines.

The test facility design addressed the requirement for providing unique mixtures of natural gas with nitrogen, carbon dioxide or propane. For example a baseline natural gas fuel would be enriched with propane or leaned out with inert components to approximate the fuel characteristics simulating specific customer fuel MWI requirements. While customer site fuels are not simple mixtures of natural gas and a pure additive gas, such blends of the same MWI are considered to be representative of the operation and control of the gas turbine under typical site conditions. It is clear that while the fuel calorific content and specific gravity can be well represented in this fashion, there will still remain some differences between customer site and test facility exhaust emissions due to differences in the actual gas constituent makeups.

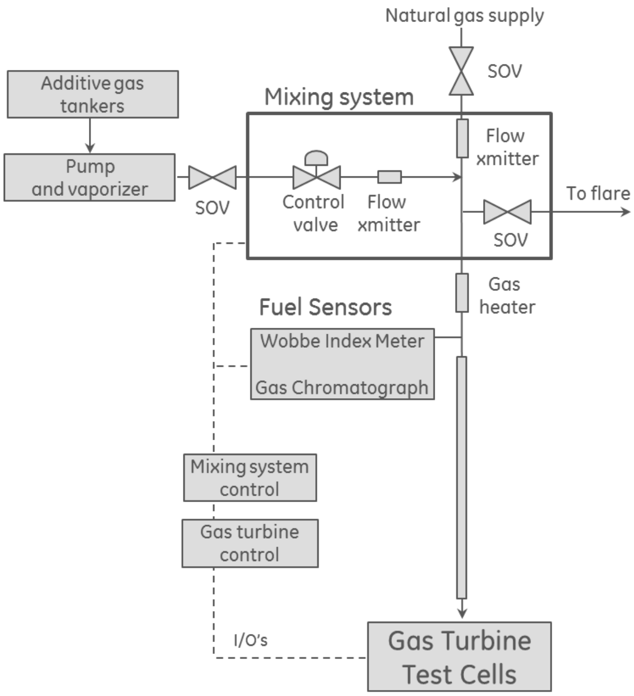

Figure 1 – Schematic diagram showing added gas and NG mixing system and location of WIM and GC analyzers

For specific full-scale full-load test conducted in 2013, the gas fuel supplied to the test cell was either pipeline natural gas or the same natural gas mixed with the specified flow rates of nitrogen (N_2) to achieve the specified MWI. The mixing of N_2 with the natural gas was accomplished with a fuel mixing system designed exclusively for fuel flexibility demonstration and development test programs and located in close proximity to the test facility.

Figure 1 presents a schematic of the gas mixing system used for these demonstration tests.

The test facility fuel delivery system was designed to supply either the site natural gas or its mixture with N_2, containing anywhere between 0 percent to 60 percent N_2 by volume at the required pressures, and fuel flow demand levels from startup to base load power. The system design allowed the operator to set the N_2 to natural gas ratio to any desired value in the range and switch the mixed gas flow to the flare, when the gas turbine was shut down. This ensured the mixed gas remained constant for the subsequent gas turbine start as seen in Figure 2.

The gas turbine control fuel flow demand signal was connected to the gas mixing system programmable logic controller (PLC). The PLC logic allowed, as fuel flow demand changed, a proportional change in N_2 along with natural gas to maintain the set gas mixture ratio throughout the entire range of power.

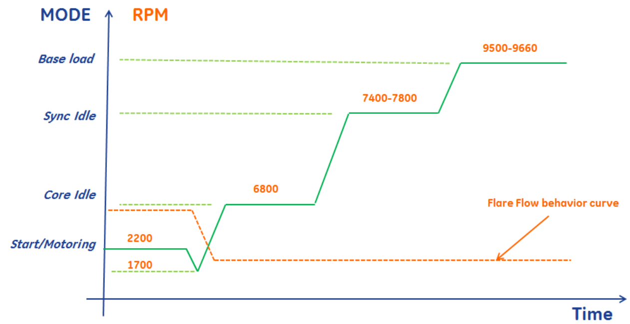

Figure 2 – LM2500+G4 start-to-base load profile vs. flare response

The facility fuel supply and mixing system has the capability for future upgrades and adjustments specific to the requisite test procedure and requirements, thanks to its modular design. This includes the capability to test to the greater fuel flow levels necessary for the LM6000PH and LMS100PB gas turbines. The inherent capability of natural gas enriching and dilution allows production of a very broad range of fuel properties. Utilization of trailer-mounted equipment for the additive gases and gas boost compression helps to lower capital expenses and maintenance costs.

The gas fuel supply and mixing system consisted of primary elements described in Table 1 below.

Basic testing criteria

Specifically, the main objectives of the test programs were as follows:

1. Create a baseline combustor map for natural gas and selected N_2/natural gas blends. Generate updated natural gas combustor flame temperature schedules for upload to the gas turbine control to replace the existing default schedules.
2. Determine the trends of emissions and flame temperature design space boundaries between incipient lean blowout and high acoustic onset as a function of MWI and load level.
3. Demonstrate acceptable system response to MWI increases and decreases at various rates of change in composition per given time period while holding constant gas turbine load.
4. Demonstrate load change from minimum to base load and back with different selected gas blends.
5. Demonstrate acceptable starting with different selected gas blends.

Equipment	Functional description
Additive gas transport and storage	Stationary or portable tank of additive component (N_2/CO_2/propane) with sufficient capacity to enable continuous supply operation and refilling in parallel
Additive gas vaporizer and pump	Modularized system for forwarding and conditioning the additive component in a desired phase
Additive gas ballast tank	Optional buffer tank for additive component gas for pressure stabilization and sustaining high flow conditions
Fuel Mixing System	Gas blending system consists of multiple isolation, flow control and pressure control valves along with flow, pressure and temperature transmitters. Maximum flows: Natural Gas 52,000 pph [23.6 tonne/hr] Nitrogen 38,000 pph [17.2 tonne/hr] NG/N_2 Blend 90,000 pph [40.8 tonne/hr] Maximum working pressure 1480 psig [102 barg]
Gas temperature control	Optional heat exchanger enabling tight control of fuel temperature
Fuel measurement system	Array of fuel sensors for composition and properties measurement, detailed in paragraphs below
Compressors	System of compression enabling required flow and pressure of natural gas
Process gas flare	22-foot [6.7 m] flare stack with an automatic pilot ignition/burner management system. The flare was used to allow system testing when the gas turbine was shut down and to depressurize the system when not in use. Additionally, the flare provided a flow to maintain a steady mix of gas at the prescribed ratio for gas turbine starting.

Table 1 – A summary of the major unit operations for fuel flex testing at GE's gas turbine test facility in Houston, USA

Description of the equipment used during the test

GE's Continuous Emissions Monitoring System (CEMS) enables measurements of NOx, CO, UHC, and O_2 concentrations in exhaust gases. Four circumferentially and equally spaced probes are used to draw continuous samples of the exhaust gas at the discharge of gas turbine exhaust. The samples from the four gas-sampling probes are combined to provide an average gas sampling and sent on to the emissions analyzers. The analyzers provide both raw NOx and CO as well as the industry standard corrected to 15 percent O_2.

For gas properties determination to verify that the gas blend produced in the mixing system fully met testing requirements, two independent gas analyzer systems were used during this test and are described in detail below.

Instrumentation requirements

GE recommends that the measured or indicated lower heating value (LHV) and specific gravity (SG) inputs to the gas turbine control shall always be within 1 percent of actual values of the gas fuel during steady-state operations and 3 percent during gas property changes. The tolerance of the control of gas turbine total fuel flow and fuel flow distribution to gas property transients is significantly affected by the fuel sensing instrument response time. Instrument response time constant (τ) for a 90 percent change in composition detected, T90, includes cumulative time required for gas sample extraction, physical analysis, and signal processing cycle of the analyzer system. The measured signal accuracy and repeatability can be affected by the type of gas sampling probe used to extract the sample, instrument response time, instrument error, calibration range, and frequency of calibration. The ability of any gas analysis instrument to rapidly determine gas properties is a critical factor to maintaining acceptable levels of operability for a DLE gas turbine.

Among the various options for fuel analyzers, a gas chromatograph and a Wobbe Index Meter were selected for the testing. A comparison of such instruments is shown in Figure 3.

Instrument	WIM	GC
Response Time	$T90_{instrument}$ < 5 secs.	3- to 4-minute analysis time
Outputs	LHV, SG	LHV, SG, %N_2, %CO_2, Specific heat ratio, Z
Repeatability	±0.05% BTU/SCF	±0.025% BTU/SCF

Figure 3 – Survey of fuel sensing instrumentation

Gas chromatograph

A gas chromatograph (GC) is widely used for gas properties determination in industry. Typically a GC, like most commercially available gas analyzers, is primarily used for gas commodity transfer and has been adopted for use as part of the gas fuel control system for gas turbine fuel flow control. Consider the example of a GC with a response time, T90 of 180 seconds. The GC has a repeatability of +/-0.025 percent and is considered a baseline device widely used to measure gas fuel composition for aeroderivative DLE gas turbine control systems. In Figure 4, the top plot is near steady-state conditions for the actual gas properties that are ideal for a gas chromatograph measurement system. The instrument response time permits only five measurements within the 900-second period. This response lag time impacts accuracy when comparing actual and reported gas properties when there is a change. The plot on the bottom side of Figure 4 illustrates the divergence in actual values to the reported values that lag the system. This occurs when a significantly fast change in gas properties exceeds the ability of the gas chromatograph to accurately represent the transient event. Although the GC is accurate under specific conditions and provides all necessary gas turbine control inputs, sustained compliance within the recommended error tolerance of the measurement system for the gas turbine controls between the reported and actual fuel properties provides little in the way of tolerance to fast variations. It is quite clear that a gas chromatograph is a fragile guidance system and presents a risk when used to avoid operability issues associated with fuel property variation.

The lower plot in Figure 4 shows the gas properties with a rising LHV that is simply not registered by the GC on a useful timeframe. A transient event as such would most certainly result in operability issues for a gas turbine. The plot emphasizes the point that a faster instrument response time is required to maintain compliance in actual and measured fuel properties.

Wobbe index meter

A faster response time can be obtained using a flameless calorimeter such as a Wobbe Index Meter (WIM). The instrument provides a Wobbe index and combustion air requirement index (CARI) number as the basic outputs. LHV and SG are available output options as well. While LHV and SG are most critical inputs to the control of fuel flow relative to maintaining good operability, additional gas properties are required by the control system to achieve the required accuracy. These include N_2 and CO_2 mole fractions, the ratio of specific heats, Cp/Cv, and compressibility. To obtain these properties' measurements, a gas chromatograph, or equivalent analyzer, must be employed in parallel. While various claims and conditions have been made by suppliers for the WIM capabilities, a response time, T90, of 10 seconds was selected for the example below. The WIM used during this test has a repeatability of +/-0.05 percent. Consider the example in Figure 5, which clearly shows the superiority of a faster response measurement system in reporting rapid transient gas property changes accurately. The faster instrument is more representative of the actual gas properties under dynamic conditions, enabling a greater tolerance to fuel variation.

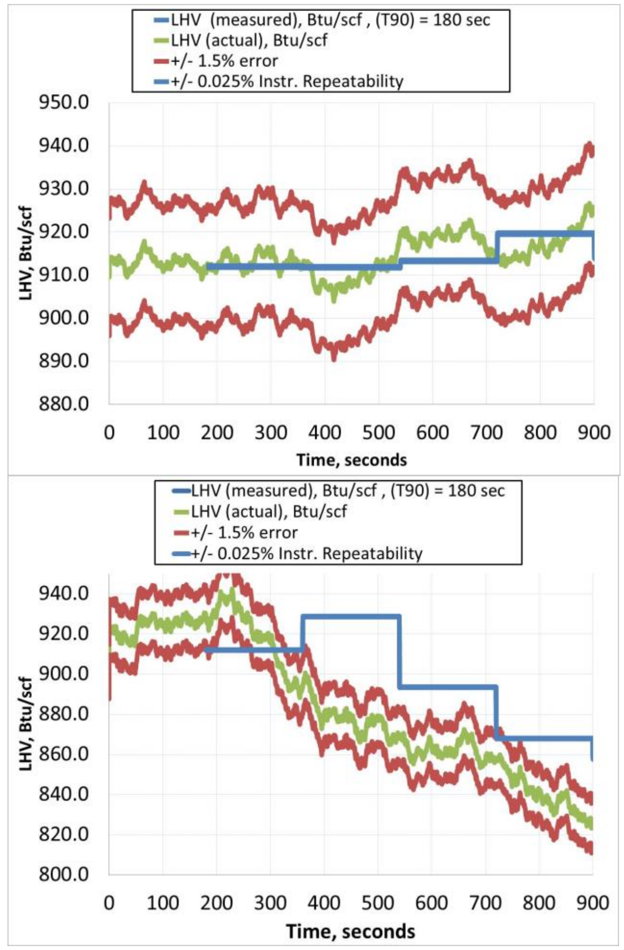

Figure 4 – GC reported value with (top) and without (bottom) compliance to +/-1.5% time-based error tolerance to gas property change

A comparison between two scenarios of transient events is shown in Figure 5. The top plot represents a slower transient, though significantly faster than what is observed for the gas chromatograph. The bottom plot in Figure 5 illustrates a divergence in accuracy for a period when the faster transient composition exceeded the WIM capability to measure the gas properties. The slower the instrument response time, the greater the lag of the reported indicated values to the actual values. The faster the transient gas composition changes, the greater the produced lag between the actual and reported indicated values for a fixed instrument response time.

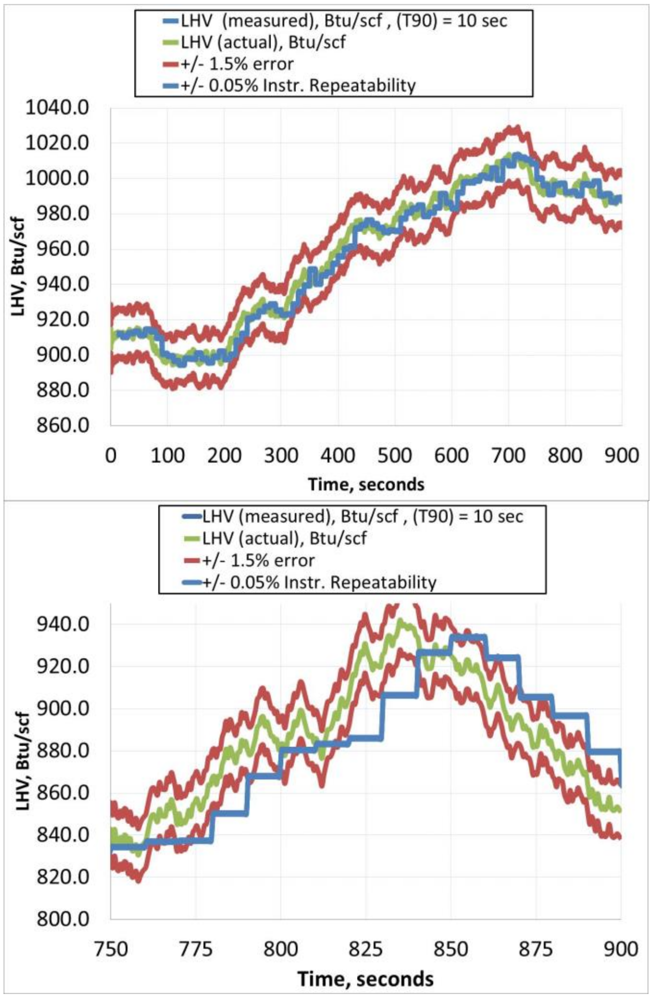

Figure 5 – WIM reported value with (top) and without (bottom) compliance to +/-1.5% time-based error tolerance to gas property change

While the GC lags beyond any practical timescale in these examples, the WIM does fall within the ±1.5 percent gas properties error tolerance target, including instrument lag time. The same lagging effect of the GC is observed with the WIM if the actual gas properties change at a faster rate than the analyzer's capability to provide the measurements, thereby defining the rate of change entitlement. This is illustrated as the WIM still fails to cover the fastest transient events. Response time capability and the maximum expected rate of change in gas composition will dictate which gas analyzer type instrument will be best suited to provide LHV and SG inputs to the gas turbine fuel control.

INSTRUMENT SELECTION AND GAS TURBINE CONTROL DEVELOPMENT PHILOSOPHY

Fuel sensor and gas property rate of change entitlement

Using the critical parameters discussed, a reasonable estimate can be made to determine a required cumulative gas analysis response time and the corresponding gas property rate of change that it enables. The plot in Figure 6 represents a simplified model for a range of sensor response time scales and the corresponding rates of change in gas properties that can be tolerated by the gas turbine. The cumulative response time of the measurement system dictates the entitlement rate of change in LHV that can be safely negotiated. The reference 100% LHV is the MWI ~52 natural gas fuel.

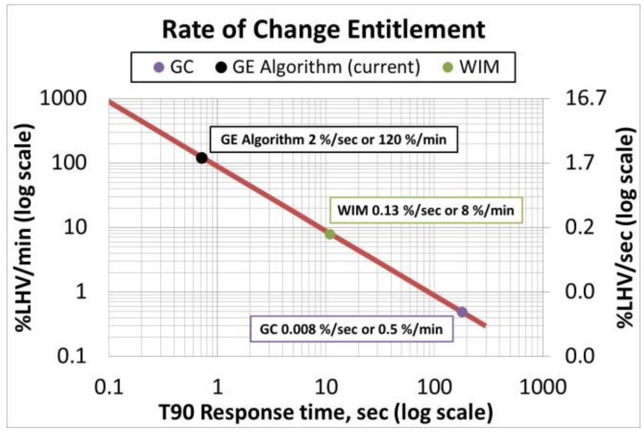

Figure 6 – Entitlement gas property rate of change for T90 response times compliant with ±1.5 percent engine tolerance to misreported fuel properties

To continuously maintain combustor operability within the acceptable range and exhaust emissions from exceeding maximum allowable levels of a gas turbine engine, the control of fuel delivery to the combustor must compensate for all changes in gas fuel properties and be transparent to the end user at any rate of change. As previously mentioned, this is particularly true for gas turbines employing lean premix dry low emission (DLE) combustion systems. DLE combustion systems require a high level of precision for fuel metering and are sensitive to changes in fuel properties, fuel lower heating value (LHV) and specific gravity (SG) in particular. The gas turbine control uses the indicated fuel properties provided by the gas analyzer, LHV and SG in particular to calculate the required fuel flow, which the control then uses to position the fuel metering valve(s).

Typical gas turbine control software can compensate for a small error percentage in LHV and SG, thus avoiding any significant impact to combustor operability or exhaust emissions. When the error is beyond this threshold, high combustor acoustics or blowout and significant power shifts can result until the measured LHV and SG catch up with the actual values of the gas at the point where the gas is being metered. The GE controls solution was developed to avoid such an adverse impact to combustor operability and exhaust emissions under these conditions. This hardware and software scheme takes into account the importance of the time to perform the gas analysis and to transmit the actual fuel properties at a sufficiently high frequency to the gas turbine control allowing the turbine to operate in the most aggressive gas property transient environments. The proprietary GE algorithm enables detection of rapid transient changes in gas composition to adjust fuel schedules appropriately at the proper time.

The fuel mixing system and the gas turbine testing facility have been instrumental in the development of gas turbine fuel control algorithms. This test platform provides a wide array of conditions in which the paramount goal of reporting actual fuel properties to the control can be investigated for a wide range of gas flows and compositions. In addition, the selection of instrumentation to be standardized into gas turbine packaging can be fully investigated in this specialized test platform. Overall, the gas mixing system has proven valuable as a low-risk dynamic testing environment in which field properties can be reproduced and mitigations identified to abate operability problems for the gas turbine and expand the new capability.

GAS TURBINE ENTITLEMENT MWI CLAIMS FOR ROC, OPERABILITY, STARTS, PERFORMANCE, AND EMISSIONS

The specialized test platform enabled the exploration of aeroderivative gas turbine fuel flexibility entitlements. Gas composition rates of change as high as **2 percent MWI per second** with seamless operability of the gas turbine were demonstrated as shown in Figure 7. A stiff linear ramp down in energy content (MWI) of gas was produced with the gas mixing system by blending nitrogen with natural gas. As illustrated, the overall operability of the gas turbine is uninterrupted for power output and maintains a compliant emissions profile. Clearly reacting to the perturbation in the fuel composition, the fuel metering valves were able to sustain the gas turbine power demand accordingly. Having successfully endured the transient event, the baseline gas was restored to the original operating conditions.

Gas turbine testing criteria are used to determine the gas turbine hardware entitlement MWI limits and rate of change over the entire power range of the gas turbine. Some key achievements such as low Wobbe gas turbine **starts at 17 MWI** (WI of 15.9 MJ/Nm^3 at 15 °C) fuel and a transition from no generator load to **base load operation at 30 MWI** (WI of 28 MJ/Nm^3 at 15 °C) are shown in Figures 8 and 9, respectively. The data for firing temperature, fuel flow, and power output have been normalized to protect proprietary information. The values for MWI and emissions such as CO and NOx at 15 percent O_2 are the actual values recorded during testing. These are the two primary goals in evaluating different fuel compositions of MWI threshold limit and the rate of change within the threshold limit from a baseline reference such as pipeline natural gas. Additional hardware testing includes gas turbine starting, full load, load accept and load rejects. Among the goals of the hardware testing is to satisfy the operability requirements of end users over a range of challenging conditions produced by the gas fuel mixing system, as seen in Figure 7, 8 and 9.

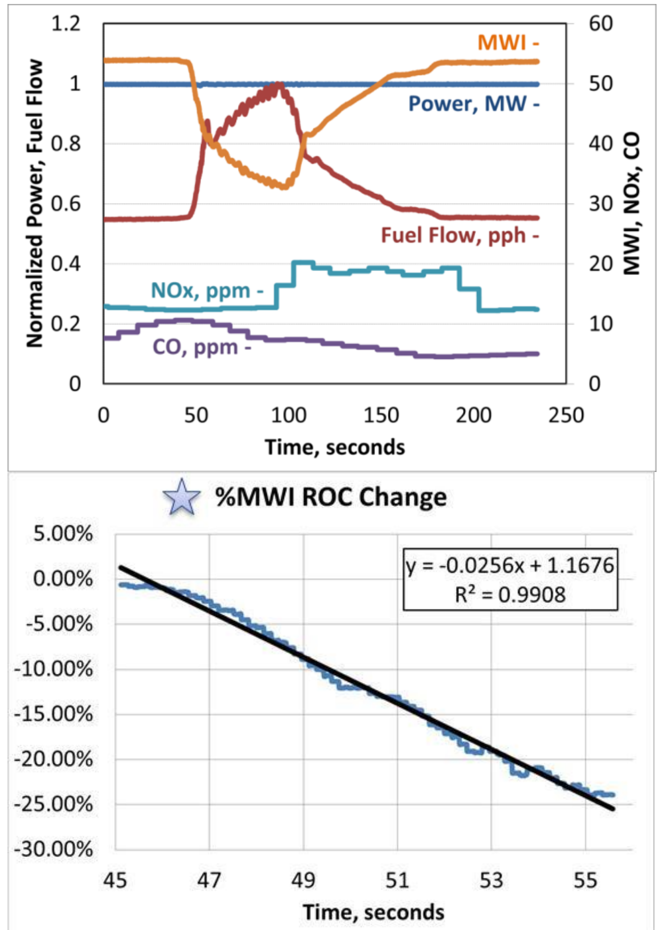

Figure 7 – Gas turbine operability during fuel composition rate of change

The low-BTU start on MWI 17 fuel is presented in Fig. 8. Before ignition (~220 sec.) the measured MWI is constant as the sensor is measuring the static fuel properties in the pipe. The increase of the MWI after the ignition is due to simulating more aggressive test conditions during start and ramp to synch idle. The main conclusion is that the startup profile (time) on MWI 17 fuel is indistinguishable from starts on natural gas.

Fig. 9 is an exemplary illustration of turbine capability to change load from 0 to maximum, while holding the MWI around 30. MWI variations represent an even more challenging scenario to the gas turbine.

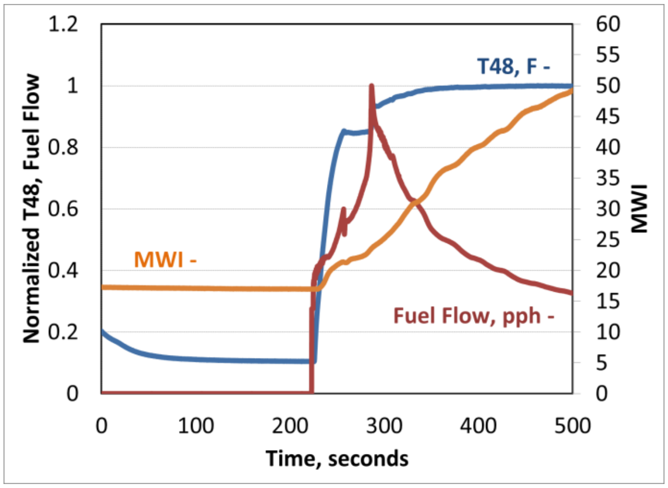

Figure 8 – 17 MWI gas turbine start

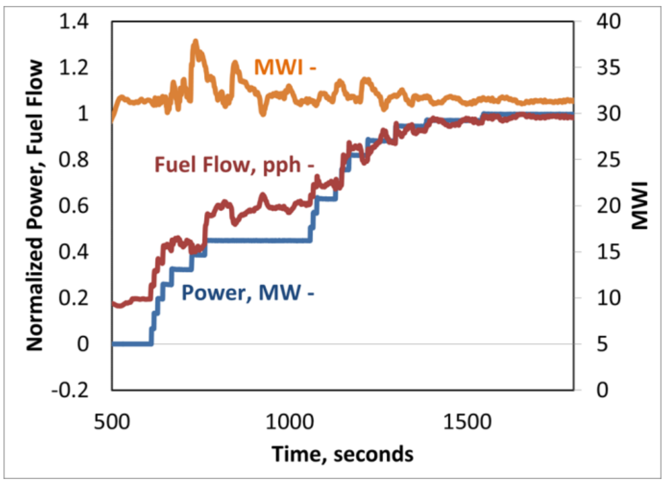

Figure 9 – Gas turbine operability on ~30 MWI fuel

While this is an impressive demonstration of dynamic capabilities, it does not necessarily represent the true entitlement levels of GE's aeroderivative gas turbines. It was determined that the limiting factors of the testing were a function of the capability of the gas mixing system and to a lesser extent the maximum obtainable natural gas supply pressure into the mixing system. In other words, the gas turbine was able to lead and negotiate the range of dynamic conditions produced by the gas mixing system. It has been shown that the ability to produce aggressive testing conditions is possible, but refinement and tighter control of gas mixing at high inert gas concentrations and higher gas pressure capability are required to investigate further the performance and operability entitlement of the gas turbine. Additional resources have been directed in the mission to determine gas turbine entitlement with a fuel system designed around pipeline quality natural gas, to explore new ideas and methods, and to push the envelope of the state of the art.

CONCLUSIONS

The incoming trend of admitting broader and variable fuel streams to gas transmission and distribution pipelines in the EU, the upsets in LNG liquefaction trains, and the use of the gas turbine to displace nitrogen rejection units are generating new challenges to combustion turbines.

In response, GE was able to survey a wide range of gas properties dynamically and then developed a step improvement in fuel capabilities. This specialized test platform and GE's technical innovations have given GE's Distributed Power business the capability to demonstrate the entitlement levels of current combustion systems, to push the envelope with non-standard fuels, and to go beyond incremental improvements in gas turbine performance. A strategic approach of testing and learning has provided a sound path of development in gas turbine technologies. The benefits of such developments will provide greater overall operability and reliability of aeroderivative gas turbines.

Specific achievements of the recent testing, enabled by the hardware and software solution developed, include an advanced fuel MWI rate of change of up to 2 percent per second, operability down to MWI of 30, and the capability to start the gas turbine with MWI 17 fuel, all with no hardware changes to the current production LM2500+G4 DLE gas turbine.

A robust gas turbine with increased tolerance to fuel variation allows end users to avoid remapping the gas turbine, so no flame schedule change is required when switching to a different gas composition. This will broaden the ability and opportunities to reliably generate power and deliver mechanical work for increasingly more challenging applications.

The significance of the new information derived from extensive testing cannot be underestimated. It will guide future design of combustion systems and control software logic for gas turbines. Fundamental experiments around rapid MWI rate of change for variable and steady-state conditions provide context for performance capability and are critical to decision making in the overall technology strategy. With this philosophy, engineering design teams can use the results of such testing to capture the performance entitlement of future gas turbines with a greater degree of understanding.

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