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AFR3 fuel system by INNIO's Waukesha Engine

Controls, Automation, Measurement, Monitoring & Predictive Maintenance

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ABSTRACT

Gas compression markets are facing economic and regulatory pressures to gain productive work out of a widening range of gaseous fuel content, variability, and location. Waukesha's AFR3 (Air Fuel Ratio 3), the next generation of fuel system technology from INNIO’s Waukesha Engine, is designed to support the full range of accepted fuels without mechanical adjustment. AFR3 replaces the carburetor with upgraded fuel valves and throttles, enabling the engine control system to adapt to changing fuel quality. Waukesha customers also need a system that is simple to install and maintain, and the AFR3 fuel system boasts a simplified fuel system setup procedure.

The AFR3 fuel system was developed in Waukesha's research and development lab and tested on fuel blends ranging from 600 to 2300 BTU/SCF. The system maintained speed and AFR targets as the fuel quality was varied up to +/- 20 BTU/SCF/sec. Field tests of the AFR3 system have accumulated over 75,000 engine hours on customer assets, demonstrating its reliability and robustness. Customers who participated in these tests have offered positive feedback on the system and enthusiasm for general availability.

This paper presents the implementation of the AFR3 system and the market challenges it addresses.

1 INTRODUCTION

Reciprocating internal combustion engines (ICE) are used extensively in the production and distribution of natural gas. They are used for extraction at gas collection sites, for compression at midstream sites, and increasingly for direct drive at drilling and exploration sites. They are also used in a variety of mechanical systems to drive loads such as generators, pumps, and assorted mechanical drives. With this wide range of uses at the forefront of the natural gas supply chain, these engines are pushed to operate in increasingly demanding, increasingly diverse environments on a widening range of gaseous fuels. Some engines use pipeline-quality natural gas as the fuel source. Others run directly on field gases which can have a wide range of quality and potentially high energy density. At the other extreme of the energy density spectrum, the fuel source can be diluted with inert gases such as commonly occur in biofuels, landfill gas, sewer gas, digesters as well as flare gas.

As the industry has expanded to include wells from new sources made possible by improvements in hydraulic fracturing technology, the fuel content experienced by a typical stationary engine has become more variable. Changes in upstream activity or the addition, decay, and removal of wellheads in the gas stream cause the fuel source to change. This variability is even more pronounced on engines used in rental fleets or operating in areas of elevated drilling activity. Figure 1 illustrates the change in the number of natural gas wells in the United States between 2008 and 2022.

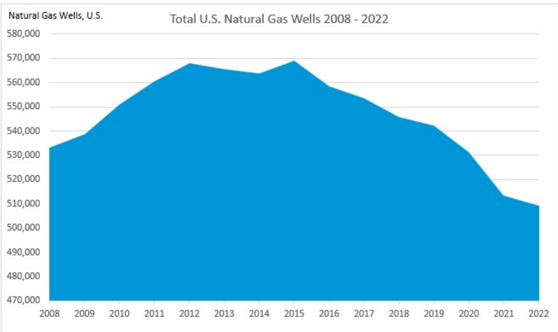

Figure 1. Total number of natural gas wells in the United States during the fifteen-year period ending in 2022 [1]

At the same time, environmental regulations have become increasingly stringent. Reciprocating ICE are required to comply with strict emissions limits in any application to which they are deployed and with any fuel used to run them [2]. Maintaining low emissions requires precise and accurate control of the air-fuel ratio (AFR) of the gaseous mixture entering the combustion chamber.

Traditional ICE fuel systems include a carburetor responsible for coarse control of AFR. These systems typically include a trim valve on the fuel upstream of the carburetor. When the fuel quality changes beyond a prescribed threshold, a trained technician is required to tune the carburetor based on the new fuel quality. This requirement takes time and planning on the part of engine fleet operators. It is reactionary, leading to a period of time when the engine operates outside optimal parameters until a technician can provide service. It also introduces the potential for human error.

To address these challenges, INNIO Group's Waukesha (Waukesha) developed the AFR3 fuel system. The AFR3 fuel system is designed to adapt to changes in fuel quality based on software inputs, without requiring mechanical adjustments to the engine. This is accomplished by replacing the diaphragm-based carburetor and fuel control valve with a full authority fuel system. The full authority fuel system leverages fuel pressure and temperature sensors not present in the traditional fuel system to deliver appropriate flow rates of fuel and air at each operating point on any fuel composition.

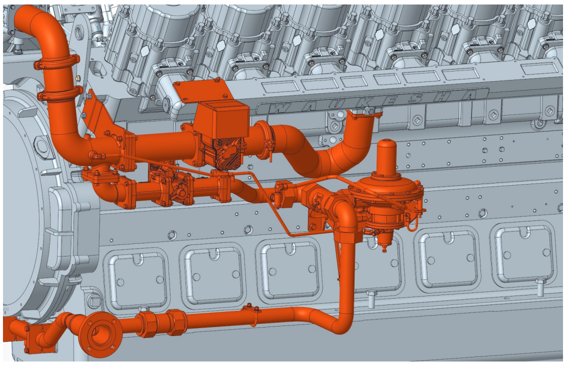

Figure 2. AFR3 fuel system design

Figure 2 shows one configuration of the AFR3 system for a Waukesha vee engine. Fuel is metered by a fuel valve and mixed with air on each bank. Each bank has an independently actuated electronic throttle that controls the air-fuel mixture entering the intake manifold. The air-fuel stream passes through three turns before entering the manifold to facilitate mixing of the air and fuel.

2 AFR3 CONTROL SYSTEM

The addition of new pressure and temperature sensors to the air and fuel systems provides an opportunity for more sophisticated control algorithms. Together, these improvements to hardware and software lead to more fuel flexibility for engine operators.

2.1 Fuel Property Variation Effects

As described above, a variety of factors are converging to widen the range of gaseous fuels used in reciprocating natural gas-powered ICE.

Alkanes form the bulk of the hydrocarbons contained in these fuel blends. These may have an average hydrogen to carbon (H/C) ratio from 4 (methane) down to approximately 2.6 (similar to propane). The fuels can also contain diluents, predominantly nitrogen and carbon dioxide, that have molar concentrations ranging up to more than 40% of the total.

This variation in fuel composition leads to a range of fuel stoichiometric air-fuel ratios (SAFR) at the engine from less than 5 to more than 25 on a molar basis. Since the lower heating value (LHV) of the fuel is roughly proportional to its SAFR, the energy density also varies over approximately a 5:1 range. Along with SAFR and LHV, other fuel properties that are important to controlling the engine change with the fuel composition. Fuel composition can vary significantly between engine sites, over time for a single engine, or where field gases or diluted blends are burned. For mobile applications, there may be substantial changes in fuel composition between engine starts as the fuel source may be vastly different because the engine has moved to a different site.

The outline in Figure 3 shows the typical spread of the ratio of specific heats (γ) as a function of SAFR across the fuel constituent combinations described. This ratio (γ) is defined as the ratio of the heat capacity at constant pressure (C_P) to the heat capacity at constant volume (C_V). The range of the ratio of specific heats (y-axis) indicates the variety of blends that can result in a given stoichiometric AFR.

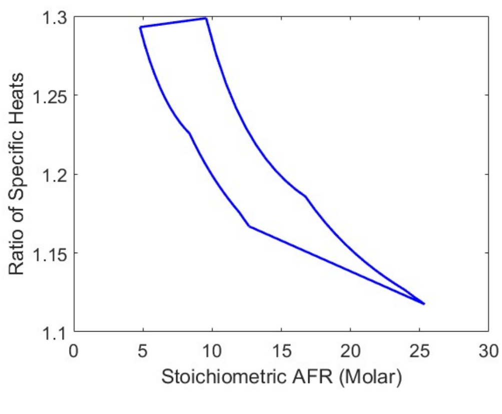

Figure 3. Range of the ratio of specific heats for fuel blends used in Waukesha engines

Figure 4 shows the variation in specific gravity (SG) of common fuel blends. The specific gravity used here is the ratio of the gas density to the density of air at a reference temperature. The specific gravity of the fuel is required for the control system to characterize the relationship between volumetric flow and mass flow of the fuel.

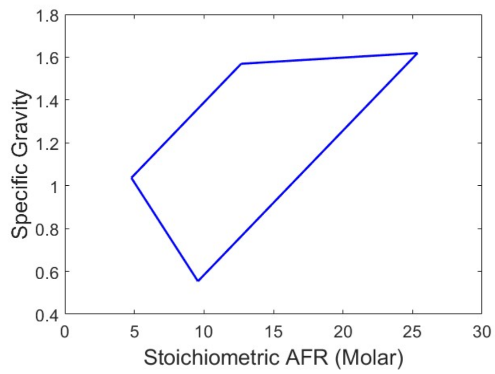

Figure 4. Range of specific gravity for fuel blends used in Waukesha engines

The current generation of Waukesha fuel controls use carburetor systems that include fixed and variable restrictions in the fuel line. Together with Waukesha's engine control strategy, the system must deal with the wide range of fuel properties described above while delivering engine performance meeting product requirements. Given this wide range of fuel properties, selecting, and adjusting the carburetor to achieve good performance can be complicated. The Waukesha engine management system (ESM2) achieves air-fuel ratio (AFR) control by adjusting a variable restriction in the fuel line leading to the carburetor fuel inlet. The current generation of fuel controls is expanded in the next section.

To illustrate the impact of the variable fuel properties on engine operation and the need for the variable restriction, the flow coefficient for the variable restriction was estimated for a constant engine operating torque and speed as the gas properties were varied. A nominal value for the flow coefficient was determined based on an assumption that methane is the fuel. The combination of carburetor parameters and gas supply pressure were chosen to provide the required engine performance over a range of operating conditions on that single fuel. However, as the fuel composition changes, this nominal combination of carburetor parameters and supply pressure are no longer appropriate. The control system accommodates by adjusting the variable restriction as the fuel blend changes. The flow coefficient, normalized by the flow coefficient for methane, is shown in Figure 5. The blue line in the figure represents a sweep in pure alkane fuels from an average H/C of 4 down to 2.6. The red line shows the same sweep in average alkane H/C except that the fuel is diluted with a 50% molar concentration of CO_2.

As the fuel SAFR changes, the variable restriction must be adjusted. For low SAFR fuels, the gradient with SAFR is significant. A fixed SAFR can be obtained with different fuel compositions though the other gas properties of these blends may be different. As an example, the effect of the different specific gravity and ratio of specific heats at a constant SAFR is reflected by the dashed line in Figure 5. The different gas properties lead to a need to change the variable flow coefficient by a factor of approximately 2:1 between pure methane (solid blue line) and an alkane blend diluted by 50% CO_2 (solid red line).

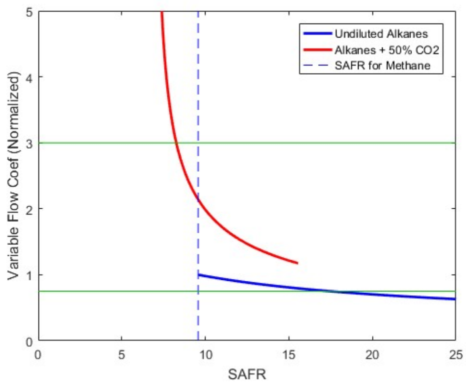

Figure 5. Variable flow coefficient for a venturi-based system on a range of fuel blends

The selection and adjustment of the fuel system components is a compromise. For example, the green lines in Figure 5 represent a potentially acceptable turndown ratio for the fuel actuator at this engine operating condition. Since the high SAFR, undiluted fuels fall outside this region, some adjustment of the fuel system may be required to achieve good engine performance when combusting these fuels. The adjustment might involve a modification of the setting of the regulated supply pressure, for example. For low SAFR fuels (low energy content fuels), the required restriction may be well outside the range of acceptable actuator adjustment. In this case, different carburetor system component hardware might be necessary.

Figure 6 shows similar estimations for the next generation fuel system. This new system uses a simple mixer in place of a carburetor and has other differences that are expanded in the next section. For the same turndown ratio, it can be seen that a single set of fuel system hardware and adjustments are feasible to cover the entire range of fuel compositions. This has been demonstrated in engine testing across this range of fuel SAFR.

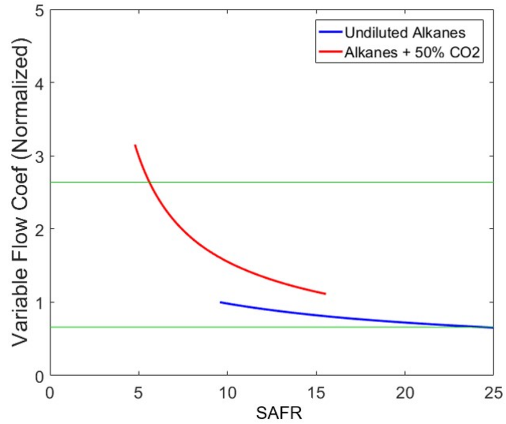

Figure 6. Variable flow coefficient for a mixer-based system on a range of fuel blends

The control system must adjust for this varying fuel pressure requirement as fuel composition changes. This must be achieved in both steady state and transient conditions to avoid inconsistent combustion. With feedback, the control can adjust the torque and AFR in steady state in a straightforward manner. However, during transient conditions, adjusting for this variation in required flow coefficient (for diluted fuels, in particular) can be more difficult.

2.2 System Architecture

With Waukesha's current generation of fuel controls (AFR2), the flow coefficient of the restriction feeding the carburetor is trimmed electronically using an actuator. Different actuators are used depending on the product, but this actuator allows the flow resistance to be adjusted by the control strategy. Figure 7 shows a typical system architecture and illustrates both low- and high-pressure applications. The supply pressure to the fuel control actuator is provided via a mechanically adjustable gas regulator. For low pressure applications in which the fuel is introduced upstream of the turbocharger compressor, the gas regulator is set to a fixed pressure. In high pressure applications, the fuel is introduced to the intake system downstream of the turbocharger and charge cooler, and the gas regulator is biased using boost pressure. Various pressures, temperatures and other engine variables are measured by ESM2. For simplicity, the figure shows only the location of sensors associated with the fuel system control.

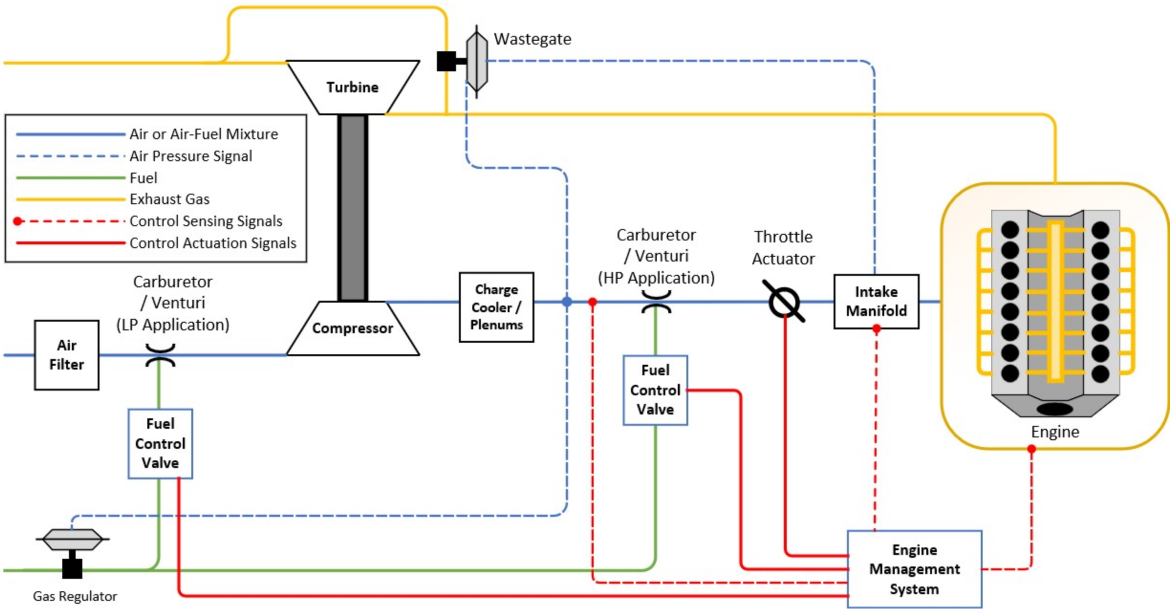

Figure 7. Carburetor-based AFR2 system

While a carburetor is capable of providing acceptable control of air-fuel ratio if properly selected and adjusted, it creates a number of challenges:

- The selection and development of fuel components (e.g., carburetor cones, fuel restriction to the venturi) can be time consuming.
- Initial commissioning of the engine, including the setup of the fuel system and initial starting, can be difficult. Further, success can require a moderate level of customer training and understanding of the fuel system operating principles.
- Re-adjustment (such as carburetor screw adjustments or a different regulator pressure) is needed if the fuel composition varies measurably.
- A single set of hardware is not usually suitable across the complete range of fuel composition. Thus, fuel system components sized for commercial quality natural gas and propane might need to be changed to run the engine on biofuels, for example.
- The lack of AFR feedback prior to the oxygen sensor reaching operating temperature makes it time-consuming to get an engine commissioned or to restart the engine following a significant change in fuel composition.
- Some AFR2 components are subject to wear (e.g., carburetor cones)
- Carburetors are not robust to mechanical loads. Thus, they are susceptible to damage in the event of large pressure pulsations in the intake system.

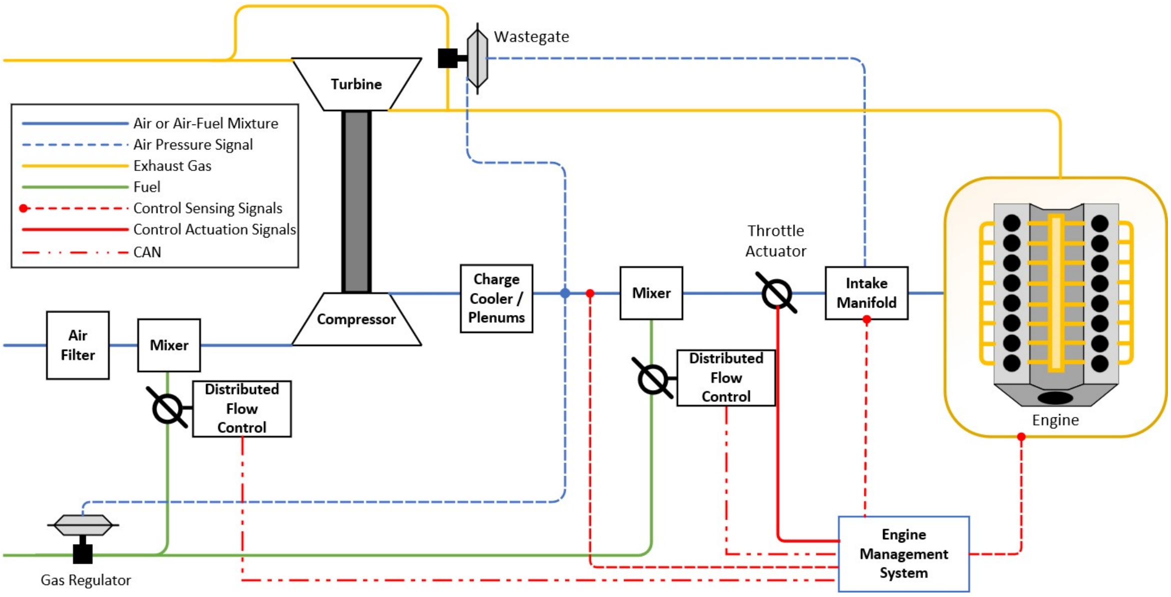

Figure 8. AFR3 fuel control system

With Waukesha's next generation of fuel controls (AFR3), the carburetor and fuel actuator are replaced with an enhanced fuel actuator and mixer. The new fuel flow actuator has embedded sensors and its own distributed controller. The local control adjusts the opening of a butterfly valve to provide fuel flow that tracks a command communicated to the actuator via a control area network (CAN). The distributed controller also provides component-level fault detection. The actuator accepts estimates of the gas properties (specific gravity and ratio of specific heats) of the fuel blend provided by the engine controller to enable more accurate control of the gas flow relative to the command. Figure 8 shows a schematic of the AFR3 fuel control system. Regulated gas pressure is provided to the AFR3 system in a similar manner to the conventional carburetor-based system.

2.3 Control Strategies

The throttle position and fuel actuator are controlled using feedforward and feedback models. While steady state accuracy requirements can be met with feedback control alone, transient response is significantly aided by feedforward terms that are based on phenomenological models.

At issue for the feedforward, or open-loop, control is the ability to deliver a fuel flow that is close to a target value in transient conditions or conditions in which feedback may not be available. In particular, this is important in achieving more dependable engine starting. The AFR2 system relies on correct fuel system setup for good starting. The commissioning procedure for the fuel system involves significant manual intervention and / or additional instrumentation. This setup procedure may need to be repeated when fuel composition changes substantially to get the mixture within flammability limits during cranking. With AFR3, the mixture can be adjusted over a wider range automatically with the span and rapid response provided by the fuel actuator. When combined with the application of relevant models to compute a target flow, the engine can be started much more reliably even if there has been a change of fuel quality since the previous shutdown.

With AFR2, closed loop controls adjust the engine air and fuel flows to deliver the AFR and torque required for regulating the engine operating point and achieving best emissions during steady state conditions. While many applications are characterized by long periods of operation under essentially steady state, some engines used for power generation and for oil / gas production are subject to frequent transient load changes. The magnitude of these load changes can also be substantial, reaching nearly 100% of the engine's torque rating. Of course, even engines that run in predominantly steady state conditions have at least occasional load changes. A properly adjusted carburetor is capable of maintaining AFR across a wide range of load conditions, even during transients. However, if fuel composition changes, the carburetor will no longer deliver the same AFR control during transients.

The AFR3 system relies fully on the control strategy to adjust fuel flow during transient conditions. While this adds some complexity to the model-based feedforward components of the strategies, since this is done using behavioral subsystem models, the result is a control system that can adapt to changing fuel properties. Excursions from the target AFR are limited during these transients, leading to improved combustion stability through rapidly changing loads. The enhanced transient control also leads to improved emissions during transient conditions.

A secondary, but not inconsequential, benefit of the selected AFR3 actuators is the ability to interface between the engine management system and the distributed controller via a direct flow command. The actuator position is controlled locally so that the estimated flow through the fuel valve tracks the commanded flow. Pressures and temperatures needed for flow estimation are measured by the distributed controller and are available to the engine management system via CAN.

Knowledge of the actual flow through the valve enables an improvement of parameter adaptation algorithms. Observers and / or Kalman filters can be used to establish better estimates of system states and / or adapt to parameters that may not be well-known or may be subject to change with environmental conditions or component aging. A limited number of these strategies will be applied with the initial AFR3 system, but additional strategies will be deployed in future releases. Goals of these strategies include improving transient response, further reducing the need for operator intervention, and providing greater insight into engine health via monitoring changes in engine parameters.

An additional feature that is enabled through the implementation of AFR3 is transient enrichment. This is particularly important for lean-burn engines to achieve faster transient response by providing more combustion torque as well as greater energy to the turbocharger during load application. It will also benefit combustion stability which is increasingly important as lean combustion limits are stretched to reduce NOx production.

3 AIR-FUEL MIXING

Computational fluid dynamics (CFD) simulations were leveraged to down select the best AFR3 concept from among several proposed engine package options. Results for only the best performing AFR3 candidate and the serial production AFR2 engine are presented and discuss here.

3.1 Transient CFD Model

The CFD model geometry consists of the engine induction system just downstream of the engine charge air cooler (CAC), the fuel delivery system downstream of the pressure regulator, the AFR3 fuel valve, the AFR3 throttle, and the intake manifold/ports of a single bank of a vee engine. Transient boundary conditions were obtained from a 1D engine model calibrated to engine data at three primary load points encompassing the range of engine speed and load observed on over 100 field units each operating over 10,000 hours.

As is common in the internal combustion engine industry [3-6], the CFD model used a RANS k-ε turbulence model to account for the effects of turbulence on mixing with a standard law-of-the-wall functions to account for wall boundary layer effects. In addition, velocity and fuel species adaptive meshing is performed at each time step to refine the mesh in regions of high local velocity gradients and at the fuel-air mixing interface, respectively.

At each load point, the CFD model is run transiently for 30 engine cycles to capture the fuel-air mixing through the AFR3 hardware, the intake manifold/ports, and to each cylinder. Results for the first 10 engine cycles are monitored to confirm stabilization of the net charge mass and overall λ delivered to each cylinder from a cycle-to-cycle basis. The subsequent 20 engine cycles are then used to calculate a 20-cycle average and standard deviation (σ) of λ delivered to each cylinder to assess the mixing performance of the AFR3 system relative to the AFR2 version.

3.2 CFD Model Results

The primary critical to quality (CTQ) metrics used to assess the performance of the AFR3 system relative to the AFR2 system are the span of maximum average λ to minimum average λ ($\lambda_{MAX-MIN}$) as well as the span of maximum possible deviation calculated as the minimum average λ minus one standard deviation ($\lambda_{MIN-\sigma}$) to the maximum average λ plus one standard deviation ($\lambda_{MAX+\sigma}$). The first metric, $\lambda_{MAX-MIN}$ defines the ability of the fuel-air mixing system to deliver, on average, a uniform λ across the bank cylinders. The second metric, $\lambda_{MAX+\sigma}$ - $\lambda_{MIN-\sigma}$, provides a measure of how resilient the system is in delivering a consistent mixture across the cylinder bank from cycle to cycle. As lean or rich excursions in λ for a poorly charged cylinder will move the engine calibration strategy away from optimal performance to mitigate misfire and or knock limits, a fuel-air metering and mixing system that can minimize the span in both of these metrics will allow engine calibration flexibility and move towards performance optimized conditions.

Figure 9 shows the transient CFD results for the AFR2 system versus the AFR3 system at the three load points considered, and Table 1 summarizes the CTQ metrics. At Load Point 1 the AFR3 system performs similarly to the AFR2 system achieving similar average λ and extrema in mixing. At Load Point 2 and Load Point 3 the AFR3 system delivers a tighter span of λ across the bank of cylinders and less than half the span of extrema as noted by $\lambda_{MAX+\sigma}$ - $\lambda_{MIN-\sigma}$.

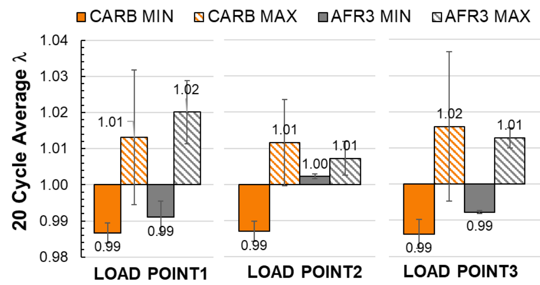

Figure 9. 20-Cycle average MIN and MAX λ with ±1-standard deviation (error bars) for AFR2 (orange) versus AFR3 (grey) fuel metering system

Table 1. CFD model results for critical to quality metrics on AFR3 versus AFR2 systems, 20-cycle averages and standard deviations

Air-Fuel Control – Load Point	$\lambda_{MAX-MIN}$	$\lambda_{MAX+\sigma}$ - $\lambda_{MIN-\sigma}$
AFR2 – LP1	0.030	0.048
AFR3 – LP1	0.030	0.042
AFR2 – LP2	0.025	0.040
AFR3 – LP2	0.005	0.010
AFR2 – LP2	0.030	0.055
AFR3 – LP2	0.021	0.024

The confidence level of the CFD results was examined in a preliminary simulation which was run 50 engine cycles with resulting deviations in the 50-cycle average λs less than 0.002 and considered acceptable. Also, it should be noted that the same boundary conditions were used for both fuel metering designs and in reality, dynamic pressure losses associated with the AFR3 design should be considered in the 1D engine model and subsequent in the boundary conditions at the intake ports. Estimates of the accuracy of the CFD model were determined through successive grid refinements and found to be less than 0.01 λ. In addition, as the turbulent mixing and charge delivery to each cylinder is predominantly driven by geometry and the engine firing order, impacts of dynamic pressure drop through the induction system are not likely to change the conclusions drawn here.

4 RESULTS

The AFR3 fuel system has been tested on all three major Waukesha engine platforms in a lab environment. The system has also been tested on gas compression skids in the field. A number of performance improvements were evident in lab test results.

4.1 Engine Starting

Engine starting performance was tested on hot and cold engines and with a variety of fuels including propane, methane, and a low BTU/SCF blend of methane and carbon dioxide. In each case, the time to reach target speed and the variability of engine speed were measured.

On one engine platform, the time to reach the speed target was reduced on average by approximately 45%. Figure 10 represents several engine starts with varied fuels and operating points. The data is normalized based on the average start time of the baseline system.

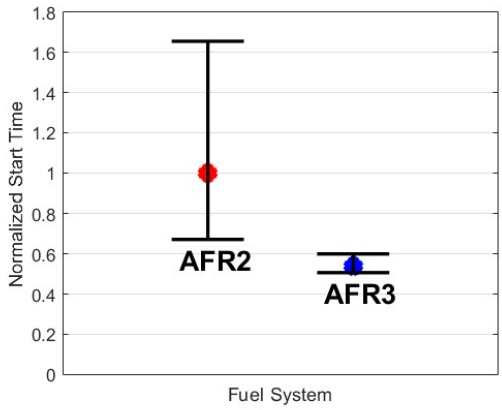

Figure 10. Average and range of normalized engine start times across various fuels and operating points

When the AFR3 fuel system was applied, the start time was significantly reduced, even such that the slowest start recorded with the AFR3 system was faster than the fast start recorded with the baseline fuel system.

The start time was also more consistent when the AFR3 fuel system was applied. With the baseline system, the standard deviation of start times was approximately six (6) seconds across all tests. When the same operating points were tested with the AFR3 fuel system, the start time was much more consistent, with a standard deviation of less than one (1) second.

This data was collected during engine starts on a single engine model across a variety of fuels and starting temperatures. The achievement of good engine speed variability was evaluated by calculating the standard deviation of engine speed in a window between 60 and 75 seconds from initiation of engine cranking.

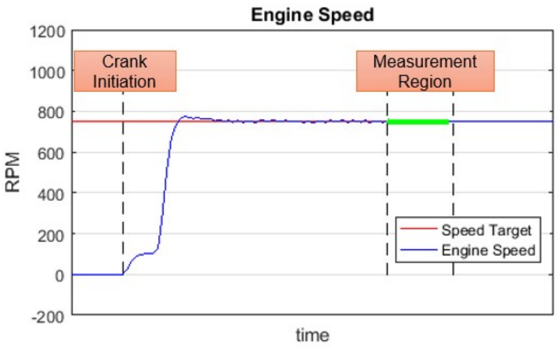

Figure 11. Speed variability criteria for engine start

When measured across the same operating points and fuels as tested above, the speed variability improved approximately 60%. This result is a direct result of faster start times. With the AFR3 fuel system, the engine started faster and reached steady-state sooner than with the baseline system.

4.2 Load Dynamics

Transient performance is critical in many applications of reciprocating ICE and most particularly in drilling rig operations, emergency standby power, and other power generation applications, among others. Improving the transient performance of natural gas-powered ICE is making it possible and increasingly attractive for operators to replace diesel engines with those powered by natural gas, reducing emissions while maintaining engine performance. Replacing diesel with natural gas also allows some operators to take advantage of readily available fuel sources and avoid the need to transport diesel fuel to the job site.

The transient performance of the AFR3 system was tested according to ISO 8528-5, which defines the number of load steps required to increase engine load from 0 to 100%. Load steps G1, G2, G3, and G4 were tested as defined in the standard. In each test, the AFR3 system outperformed the AFR2 baseline.

Figure 12 shows test data collected with the AFR3 system during the G4 load sequence. The top line in the figure is the normalized engine speed, the middle line is engine load, and the bottom lines are the left and right bank throttle positions.

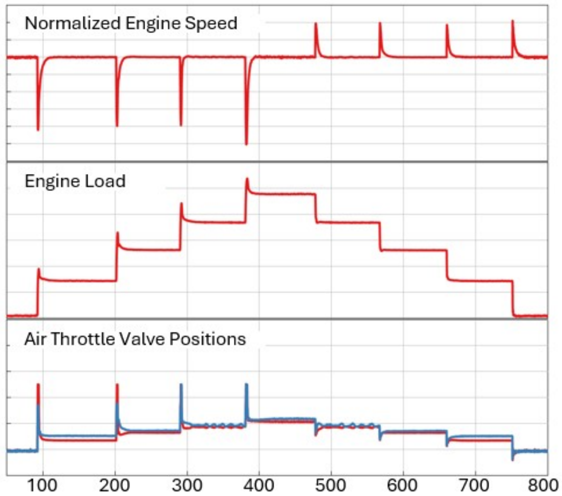

Figure 12. AFR3 load step performance per G4 sequence defined by ISO 8528-5

Most notably, the AFR3 system was able to complete the G4 test in four steps, whereas five steps were required with the AFR2 system. Table 2 shows load steps recorded for each of the four test sequences.

Table 2. ISO 8528-5 load steps in percent load for G1-G4 with AFR2 and AFR3 systems

Load Step	G4 Load %		G3 Load %		G2 Load %		G1 Load %	
	AFR2	AFR3	AFR2	AFR3	AFR2	AFR3	AFR2	AFR3
Step 1	25	31	30	37	35	40	38	45
Step 2	20	24	30	26	32	33	34	34
Step 3	20	23	25	25	27	27	28	21
Step 4	20	21	15	12	06			
Step 5	15							

4.3 Fuel transients

Fuel flexibility was a primary focus for test efforts on each engine platform. The data presented here was gathered by varying the engine fuel while running at rated engine power (speed and load).

Low LHV fuels were tested by mixing methane with increasing levels of CO_2 thereby decreasing the energy content of the fuel. The rate of change of the lower heating value varied from -20 to +10 BTU/SCF/sec. The Waukesha Knock Index (WKI) of the fuel was provided to the control system electronically by laboratory infrastructure.

High LHV fuels were tested by mixing methane with increasing quantities of propane thereby increasing the energy content of the fuel. The rate of change of the lower heating value varied from -20 to +20 BTU/SCF/sec during this test.

The standard deviation of the engine speed was calculated during two periods: while the fuel quality was changing and during a two-minute steady-state period after the fuel stopped changing. The speed and load targets were held constant, and the maximum speed control error was recorded in each case.

Table 3 summarizes the fuel quality tests performed with the AFR3 system. The first column shows the range over which the fuel was varied during the test. The second column indicates the length of time in which the fuel was ramped from the starting blend to the target. The third column shows the maximum absolute value of the difference between engine speed and speed target during the test.

Table 3. AFR3 engine speed variability during changes in fuel quality.

BTU/SCF	Ramp Time, sec	Speed Error, rpm
950 → 1280	45	20
1280 → 950	40	50
1280 → 2300	120	15
2300 → 1280	100	15

5 CONCLUSIONS

The modifications to engine components and control strategy detailed herein have led to tangible benefits in the operation of reciprocating natural gas engines. With AFR3 technology, reciprocating ICE run smoother and more consistently as fuel quality changes.

In addition to the quantitative results provided above, several forms of qualitative results were collected during development.

Technicians at Waukesha's research and development lab reported more reliable starts and improved transient control on some engine models. The system has surpassed a total of 90,000 engine hours in the field. Engine operators that participated in field trials indicated improved uptime and reduction or elimination of the need for adjustment after commissioning. One trial customer observed extended life of other engine components, which may be attributable to smoother, more consistent starting and running. They also indicated indirect benefits of the independently controlled electronic throttles such as better bank-to-bank balance, reductions in bank-to-bank adjustments, and improvements in component reliability.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR: Air-Fuel Ratio

AFR2: Waukesha's current generation fuel control system (including fuel system hardware and associated AFR control strategies)

AFR3: Waukesha's new generation fuel control system

BTU: British thermal unit, a unit of measurement for energy

CAC: Charge air cooler

CAN: Control area network (a serial data communication protocol)

CFD: Computational fluid dynamics

CTQ: Critical to quality

ESM2: Engine System Manager 2 (Waukesha's current generation engine management system)

H/C: Hydrogen to carbon ratio (the average ratio of hydrogen atoms to carbon atoms of the hydrocarbon constituents of the fuel blend)

ICE: Internal Combustion Engine(s)

ISO: International Organization for Standardization

LHV: Lower heating value (a measure of energy content per unit of fuel)

SAFR: Stoichiometric AFR

SCF: Standard cubic foot, a unit of measurement for volume or quantity of gas defined at a standard pressure of 1.0 atm (101.325 kPa) and 60 °F (15.56 °C)

SG: Specific gravity

Turndown: Ratio of the maximum to minimum adjustment (e.g., of an actuator)

WKI: Waukesha Knock Index, a unit of measurement for the propensity of gaseous fuels to cause engine knocking

γ: Ratio of specific heats

λ: Air-Fuel Ratio

σ: Standard Deviation

1D: one-dimensional

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