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LOW EMISSIONS POWER GENERATION USING NATURAL GAS CONDENSATES

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ABSTRACT

A Lean, Premixed, Prevaporized (LPP) combustion technology has been developed that converts liquid fuels into a substitute for natural gas. This fuel can then be burned with low emissions in virtually any combustion device in place of natural gas. This technology offers the possibility of using unprocessed oil-field Natural Gas Condensate (NGC) for local or export power generation using a DLN-equipped gas turbine rather than flaring, as is common practice in some regions.

The ability to run a turbine on natural gas condensate with NO_x and CO emissions comparable to those of natural gas has been demonstrated using a surrogate fuel made up from a mixture of naphtha (representing C₄ and greater) and methane (representing <C₄). The naphtha was vaporized using an LPP system, mixed with methane, and used to generate power in a 30kW Capstone C30 microturbine. The LPP Gas™ was tailored to match the modified Wobbe Index (MWI) of methane. NO_x emissions in pre-mix mode on the surrogate NGC fuel were sub 5 ppm, indistinguishable from those when running on methane. CO emissions were sub 20 ppm, comparable to those on methane. At lower loads (in diffusion mode), NO_x and CO emissions on surrogate NGC-based LPP Gas™ remain comparable to those on methane. No changes were required to the DLN gas turbine combustor hardware.

Keywords: natural gas condensate, NO_x, CO, dry low emissions, lean premixed prevaporized

INTRODUCTION

Natural gas condensate is a low-density mixture of unstabilized liquid hydrocarbons that are present in the production fluids recovered from many fields, and in many locations where there is little or no market for these liquids, natural gas condensate is wastefully flared. However, this stream, either as a pure liquid or as multiphase mixture of gas and liquid, provides an opportunity to generate electricity, process steam, or both. Each field-produced condensate has its own unique composition, depending not only on the mix of raw hydrocarbons in the reservoir, but also the design and operating parameters of the production facility. However, in general, gas condensate has a specific gravity ranging from 0.5 to 0.8 and may contain a variety of compounds such as: linear and branched alkanes having from 2 to 12 carbon atoms (denoted as C₂ to C₁₂), cycloalkanes such as cyclohexane, aromatics (benzene, toluene, xylenes and ethylbenzene) and various other compounds like hydrogen sulfide (H₂S) and CO₂ [1].

In order to take full advantage of this fuel source, it is desirable to vaporize the liquid components and burn the resultant gas in a Dry Low NO_x (DLN) combustor. This allows utilization of maximum available energy with the minimum emissions. The resultant fuel will have a composition very different from natural gas however, and will have different combustion properties. The impact of fuel gas composition on combustor performance has been extensively studied. In general, the addition of higher hydrocarbons to natural gas (methane) results in reduced ignition delay time and increased flames speeds [2-6], which may have impacts on flashback and

combustor dynamics depending on the design of the fuel injectors and combustion system [7]. These effects may be mitigated, however, by dilution of the fuel with an inert gas such as nitrogen [8, 9]. This process, namely prevaporization and mixing with an inert diluent with subsequent premixed combustion (referred to as the “LPP” process, for “Lean, Prevaporized, Premixed”), has been developed and demonstrated for a wide range of liquid fuels [9-11].

Application of the LPP process to NGC involves the addition of diluent to the raw gas stream to control both the Wobbe Index and dew point of the fuel mixture, and subsequently heating to ensure that the mixture is maintained at a temperature safely above the dew point. In this way, a DLN equipped gas turbine may be used to burn field-produced NGC or even raw natural gas (i.e. rich field gas or associated gas) without the need for a separation plant. In this work we investigate the feasibility of operating a DLN equipped gas turbine on such a NGC derived fuel gas.

LPP TECHNOLOGY OVERVIEW

A patented fuel vaporization and conditioning process [10] has been developed that achieves low emissions (NO_x , CO and PM) comparable to those of natural gas while operating on liquid fuels. In this approach, liquid fuel is vaporized in an inert environment to create a fuel vapor/inert gas mixture with combustion properties similar to those of natural gas. Properties of the fuel mixture, referred to as “LPP GasTM”, such as dew point, Wobbe Index, and autoignition tendency are controlled by the level of inert gas added during the vaporization process. The LPP GasTM can be used as a substitute for natural gas in potentially any combustion device originally designed for natural gas, including DLN combustion systems. This allows the achievement of state-of-the-art NO_x and CO emissions with liquid fuels without water addition. Tests conducted in both atmospheric and high pressure test rigs utilizing commercial swirl-stabilized burners (designed for natural gas) found operation similar to that achieved when burning natural gas [9, 11] with LPP GasTM derived from a range of liquid fuels (fuel oil #1 and #2, Biodiesel and F-T synthetic JP-8). Extended lean operation was observed for the liquid fuels due to the wider lean flammability range for these fuels compared with natural gas.

Liquid fuel is supplied to the LPP fuel conditioning skid using a fuel pump and is pre-heated (the amount of pre-heat depends on the liquid fuel being used) in order to reduce the heat input required to the vaporizer. The fuel is introduced into the vaporizer along with an inert gas and heat sufficient to vaporize the liquid fuel. The inert gas may be nitrogen, oxygen depleted air, exhaust gas or carbon dioxide, although testing to date has used nitrogen and nitrogen with a small amount of oxygen. In laboratory testing the heat has been applied to the skid using electrical heaters. However, electrical, thermal, waste heat or any combination thereof can be used to provide

energy for fuel heating and vaporization. In order to maximize system efficiency for commercial application, waste heat utilization is the preferred method to supply heat to the skid. A laboratory LPP skid is shown in Figure 1. The body of the vaporizer (wrapped in insulation) can be seen in the center-left of the picture. Pre-heated diluent (nitrogen and oxygen supplied from high pressure gas cylinders) enters from the top, as does pre-heated fuel. The heat-traced LPP GasTM transfer line connecting the vaporizer to an atmospheric pressure lean, pre-mixed burner mounted vertically with a quartz liner can be seen on the right side of the picture.

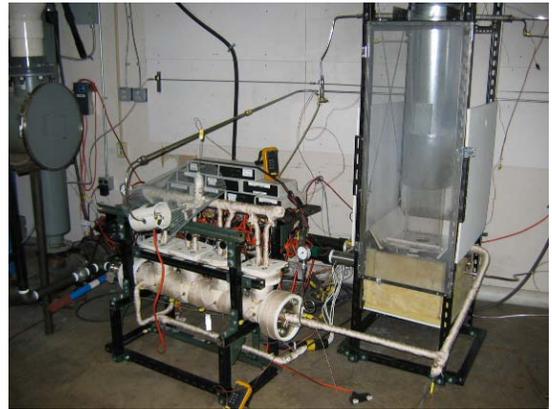


FIGURE 1: LPP SKID AND ATMOSPHERIC PRESSURE TEST RIG WITH DLN BURNER

EXPERIMENTAL PROCEDURE

An LPP GasTM derived from a mixture of methane, nitrogen, and naphtha was prepared using a lab-scale LPP system and burned in a Capstone C30 microturbine. The Capstone C30 is a 30 kW power generation system designed for use with natural gas. In premixed combustion mode, it produces nominally 9 ppm NO_x and 30 ppm of CO. The C30 operates in diffusion mode at lower loads, with the transition to premixed mode occurring between 20 and 25 kW. The combustion system operates at approximately 4 atm. An LPP system was developed that interfaces with the natural gas fuel feed of the turbine, allowing for operation on LPP GasTM, natural gas, or a mixture of the two. Figure 2 shows the test facility developed for the C30 testing, and Figure 3 shows a schematic of the LPP vaporizer and connection to the C30. Nitrogen and methane flows into the vaporizer are supplied under pressure and regulated using mass flow controllers. Pre-heated liquid naphtha is pumped at high pressure (690 to 1379 kPa or 100 to 200 psi) through a control valve, rotometer, and nozzle into the vaporizer, which is electrically heated. The LPP GasTM exiting the vaporizer is conducted to the microturbine

through heat traced tubing. A high temperature control valve interfaced to the C30 control system meters the flow of LPP Gas™ into the turbine. The exhaust from the turbine is sampled from the 10.2 cm (4 in) diameter stack at a location 2 m from the turbine exit. The sample probe is a 6.4 mm (1/4 in) stainless steel tube located at the centerline of the stack. The sample is conducted to a suite of Continuous Emissions Monitors (CEMs) using 6.4 mm (1/4 in) Teflon tubing. NOx (chemiluminescent), CO (NDIR), and O₂ (paramagnetic) analyzers are used to provide measurements of NOx and CO corrected to 15 % O₂ with estimated uncertainty of ±1 % at 50 ppm and ±10 % at 5 ppm levels. A cold trap is used to remove water before the measurements, so the results are reported on a dry basis.

Natural gas condensate composition is highly variable, depending on the individual well, the point in time in its production history, and many other factors. For this study a “raw” NGC composition rich in non-methane hydrocarbons was chosen (see Table 1). This is a typical Middle East sour associated gas derived NGC [12]. Dilution of the raw NGC with nitrogen changes both the dew point of the mixture and the Modified Wobbe Index (MWI) of the mixture, a convenient metric for comparing gaseous fuels at different temperatures [13], defined as:

$$MWI = \frac{LHV}{\sqrt{(SG \times T)}}$$

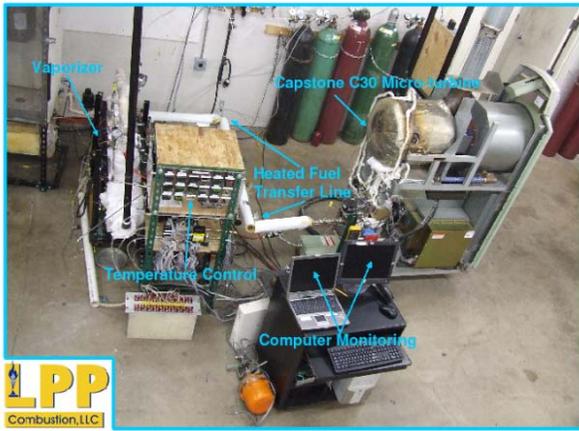


FIGURE 2: CAPSTONE C30 TEST FACILITY USED TO EVALUATE EMISSIONS FOR VARIOUS FUELS USING THE LPP COMBUSTION TECHNOLOGY.

where *LHV* is the fuel gas lower heating value (BTU/ft³), *SG* is the fuel gas specific gravity relative to air, and *T* is the fuel gas absolute temperature (R). Although no one metric is optimal for predicting all aspects of a fuel’s performance in a lean, premixed combustion system, MWI is a convenient and commonly used basis for comparison of different fuels in a given combustion system. The variation of dew point, calculated using SUPERTRAPP [14], and temperature required to match the MWI of methane (53.5) at 288 K (59 F), based on 14 K (25 F) of superheat, with nitrogen dilution is shown in Figure 4. The minimum temperature and nitrogen dilution occurs at the crossing point at about 20% nitrogen and 400 K. Lower nitrogen dilution requires temperatures above the dew point to match methane MWI, and involves a trade-off between heating and nitrogen costs. Higher dilution requires temperatures below the dew point to match methane MWI: in this case the MWI criterion must be relaxed.

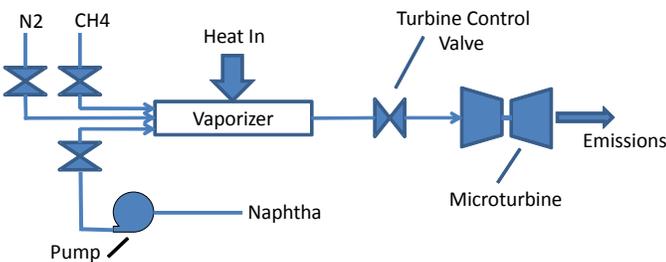


FIGURE 3: SCHEMATIC OF LPP VAPORIZER AND CAPSTONE C30.

Raw NGC		NGC LPP Gas™		Surrogate LPP Gas™	
	Vol %		Vol %		Vol %
N2	-	N2	25	N2	27
CO2	5	CO2	4	C1	35
H2S	4	H2S	3	Naphtha	38
C1	19	C1	14		
C2	17	C2	13		
C3	24	C3	18		
C4	16	C4	13		
C5+	15	C5+	10		
Total	100	Total	100	Total	100
MW	43.5	MW	39.6	MW	51.4

TABLE 1: NATURAL GAS CONDENSATE AND LPP GAS™ COMPOSITIONS

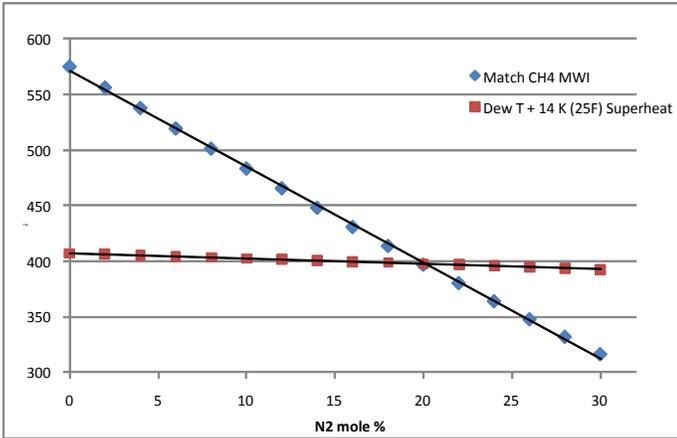


FIGURE 4: VARIATION OF LPP GAS™ DEW POINT AND MWI WITH NITROGEN DILUTION

A surrogate NGC based LPP Gas™ was prepared by blending methane, nitrogen, and vaporized naphtha. The composition of naphtha is shown in Figure 5, in which the species distribution is plotted by molecular weight for the major component classes: alkanes, aromatics, and cycloalkanes. The naphtha composition by class is alkane 95.5 mol %, aromatic 4.499 mol %, and cycloalkane 0.001 mol %, with total molecular weight of 100.4. This distribution was determined by matching measured molecular weight, class composition, and distillation curve [15]. The naphtha to methane ratio was chosen to roughly match the $C_{3+}/(C_1, C_2, 0.5C_3)$ ratio of the parent NGC. The nitrogen dilution was chosen to roughly match the MWI of methane at 288 K (59 F) with LPP Gas™ delivery temperature of 523 K (482 F) (4% difference in MWI). The surrogate LPP Gas™ composition is shown in column 3 of Table 1. Column 2 shows the composition of a similar NGC derived LPP Gas™ which has a MWI of 50.7 (5% lower than methane) at 395 K (252 F) (dew point plus superheat temperature from Figure 4).

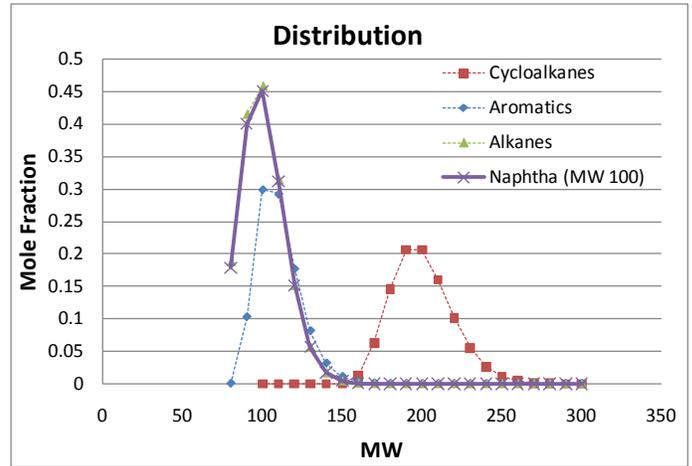


FIGURE 5: NAPHTHA COMPOSITION (MOLE FRACTION VS MOLECULAR WEIGHT) NORMALIZED TO UNITY FOR EACH COMPONENT CLASS

RESULTS

NOx emissions (ppmv corrected to 15% O₂) at 5 different loads are reported in Table 2 for C30 operation on methane, naphtha (vaporized with 82% N₂ (by volume) with a resultant MWI of 23.2, ~50% of the cold methane value), and surrogate NGC LPP Gas™. The three methane runs were made on separate days over a span of several weeks, and serve to provide an estimate of the error in the data. This error includes factors such as measurement error and day to day differences in turbine operation due to variation in ambient temperature, pressure, and humidity. Within the error of the data, there is no difference in the NOx emissions between the three fuels in either the diffusion or premixed combustion modes. This can be seen in Figure 6, in which the average value of the NOx emissions for the three methane runs is plotted with the naphtha and surrogate NGC LPP Gas™ NOx data. Note that in the premixed mode NOx levels are below 5 ppm in all three cases.

Load	Run 1	Run 2	Run 3	AVG	STDEV	Error	Naphtha	LPP Gas
[Kw]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[%]	[ppm]	[ppm]
5	50.85	43.53	50.39	48.26	4.10	8.49	39.64	
10	53.84	49.17	54.22	52.41	2.81	5.37	52.14	48.02
15	61.12	53.12	59.79	58.01	4.28	7.39	56.54	53.74
20	66.65	58.77	55.91	60.44	5.56	9.20	73.45	67.84
25	3.46	3.04	4.04	3.51	0.50	14.35	3.95	3.30

TABLE 2: NO_x EMISSIONS (PPMV CORRECTED TO 15% O₂) FOR METHANE, NAPHTHA, AND SURROGATE NGC LPP GAS™

Load	CH4	Est Error	Naphtha	LPP Gas
[Kw]	[ppm]	[ppm]	[ppm]	[ppm]
5	87.38	46.7	75.29	
10	45.48	37.4	38.42	50.68
15	39.18	30.1	27.04	35.01
20	28.41	24.1	16.86	27.66
25	39.67	19.4	5.74	12.91

TABLE 3: CO EMISSIONS (PPMV CORRECTED TO 15% O₂) FOR METHANE, NAPHTHA, AND SURROGATE NGC LPP GASTM

The CO emissions for C30 operation on methane, naphtha, and surrogate NGC LPP GasTM are shown in Table 3. The error in the CO measurements is larger than that of the NO_x measurements due to the fact that variation in ambient temperature can have a large effect on CO emissions [16]. In an effort to quantify this error the error estimates in Table 3 are based on 9 sets of measurements using various fuels over multiple days. As can be seen in Figure 7, the CO emissions from the three fuels fall within the error bars except for the high load case, for which the methane data point appears to be an outlier.

No operability issues were noted on either of the LPP fuels (naphtha or surrogate NGC LPP GasTM). There were no instances of flashback (in premixed mode) or increased combustion dynamics, and the transition between diffusion and premixed modes was normal.

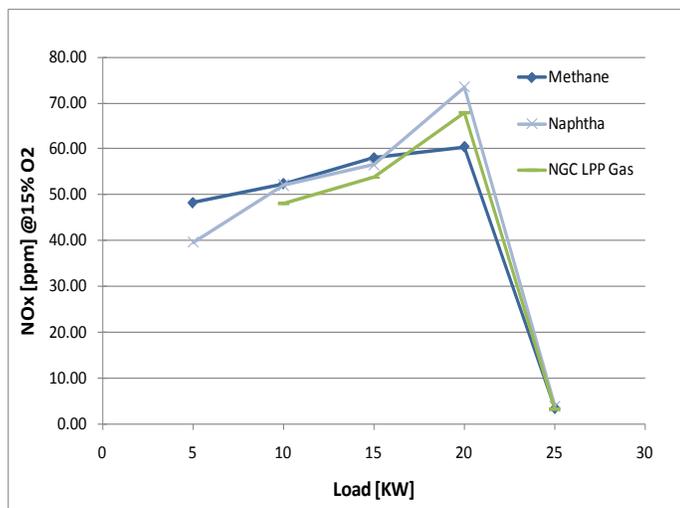


FIGURE 6: NO_x EMISSIONS (PPMV CORRECTED TO 15% O₂) FOR METHANE, NAPHTHA, AND SURROGATE NGC LPP GASTM

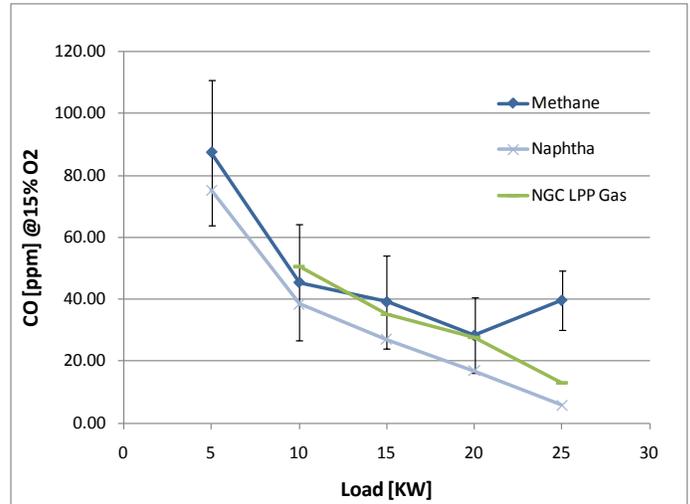


FIGURE 7: CO EMISSIONS (PPMV CORRECTED TO 15% O₂) FOR METHANE, NAPHTHA, AND SURROGATE NGC LPP GASTM

CONCLUSIONS

In this work we have demonstrated that a NGC derived LPP GasTM that uses both gas and liquid fractions can be burned in a gas turbine designed for DLN operation on gas only. These results were obtained using a Capstone C30 microturbine, and are similar to those observed for a variety of liquid fuel derived LPP GasesTM tested using a Solar Turbines Centaur 50 fuel injector (also designed for DLN operation on natural gas) [9].

- NO_x emissions for the surrogate NGC were less than 5 ppm in premix mode. CO emissions were less than 20 ppm in premix mode.
- No impact on operability (flashback and dynamics) was observed.
- NO_x and CO emissions are the same as those for natural gas operation in both diffusion and premixed combustion modes.

Operation of a gas turbine on a NGC derived LPP GasTM allows utilization of raw production gas, rich associated gas, or NGC for power generation or mechanical drive applications without the need for typical fuel gas processing. Such an arrangement could not only supply power to field operations and the local community, but also serve as a monetization method for these unstabilized liquids where project economics do not support fractionating them into standard products.

ACKNOWLEDGMENTS

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