Investigation of Atomization, Mixing and Pollutant Emissions for a Microturbine Engine

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Christopher Bolszo's research began with a strong interest in studying thermodynamics, fluid dynamics, and combustion, and their roles in energy generation and the environment. This interest led him to his research on reducing pollutant emission levels in turbine generators under the guidance of Professor Samuelsen. Christopher, now a graduate student at UCI, hopes to expand on this work and produce results that can be applied to advanced liquid fueled gas turbine systems. He describes his undergraduate research experience as a "very rewarding opportunity to venture into the forefront of engineering," a venture he hopes to build upon in the future.

Abstract

Small gas turbine engines, referred to as a microturbine generators (MTGs), produce up to 500kW of electrical power and are ideal for distributed power generation applications. By generating power where it is used (e.g., a commercial office building), using MTGs can increase the reliability and quality of the electrical power and allow the waste heat to be used to meet other energy requirements at the site. Combining electrical power generation with waste heat recovery, referred to as combined heat and power, substantially increases the overall efficiency of the unit and significantly reduces the mass emission of air pollutants per kW-hr of power generated when compared to traditional reciprocating backup devices. This project addresses this issue experimentally by characterizing the pollutant emissions from a liquid fueled MTG (Capstone model C30), and establishing the extent to which the fuel preparation processes and operating parameters affect air pollutant emissions. The results reveal that the MTG selected produces low levels of pollutants compared to other technologies currently used. Furthermore, the research critically examines the steps associated with preparing the liquid fuel for combustion to identify further potential emissions reductions, demonstrates that emissions can be further reduced, and identifies a strategy to achieve the reduction.

Faculty Mentor

The majority of electric and motive power production in the world today uses combustion to transform the chemical energy bound in the fuel into thermal energy that can drive a piston, turn a turbine, or produce steam. Combustion is also responsible for the majority of the air pollutant and global climate change gases emitted into the troposphere. The reduction of pollutant impact from combustion is closely tied to the preparation of fuel and the mixing of the fuel with air. This paper provides a basic understanding of the role of fuel air mixing in a liquid-fueled gas turbine engine and represents a major accomplishment by an undergraduate in the conduct of energy research.

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Key Terms

- Airblast Plain Jet Atomizer
- Distributed Power Generation
- Equivalence Ratio
- Evaporation Time
- Lean Premixed Prevaporized Combustion
- Microturbine Generator
- Sauter Mean Diameter
- Weber Number

Introduction

As the demand for energy increases, the ability of traditional power generation strategies and power distribution infrastructure is being challenged. In the traditional approach, central station power generation, power is generated at a few large plants and then transmitted over miles of wires known as a grid. Under an emerging concept, distributed power generation, power is produced at the locations where it is ultimately used, including commercial office buildings, schools, hospitals, and industrial plants. Although this approach reduces the loss of power across the grid, it also results in the emission of air pollutants in the immediate vicinity of people. Small gas turbine engines, called microturbine generators (MTGs), which produce up to 500kW of electricity, provide an option for distributed power generation (Borbeley et al., 2001; Smith, 2001).

Distributed generation is already accepted as a form of backup power. Backup generators are viewed strictly as insurance against power failure with the hope they will never be operated. As a result, it is difficult to justify large capital investment in these devices. Reciprocating diesel engines are a common choice, since their large scale production allows for a lower cost. While these devices can provide power when needed, they generate substantial amounts of pollution, require considerable maintenance and are often unreliable.

MTGs offer an attractive option for reducing pollutant emissions in comparison to reciprocating systems (Miller, 2004). Additionally, MTGs can produce power continuously, increasing the reliability of the electrical power to the facility. Furthermore, these devices can operate on liquid byproducts to produce power from waste, an increasing value as the cost of natural gas rises.

A major issue with MTGs is that, because they are operated continuously around people, their emissions must be minimized. The goals of this research are to characterize the air pollutant emissions from an MTG and to establish the extent to which the emissions are minimized by varying key parameters (load, combustor fuel to air ratio, atomization of the liquid fuel, fuel and air mixing, and reaction temperature) known to affect emission performance. The main pollutants of concern are nitrogen oxides (NO_x) and carbon monoxide (CO).

A 30 kW Capstone Model C30 MTG, a widely used MTG, was selected for this study (Figure 1). This model, like other turbine engines, incorporates an injection method to prevaporize and premix fuel and air prior to combustion. Within each fuel injector (three in the C30), the fuel droplets are formed by an air-blast plain jet atomizer, which uses high velocity gas (typically air) to break up a sheet or column of liquid into a fine mist (Figure 2).

The air used for combustion enters primarily through four openings surrounding the air-blast nozzle, improving mixing before ignition. Downstream of the atomizer is the swirler, a collection of vertical slots that aids in mixing and

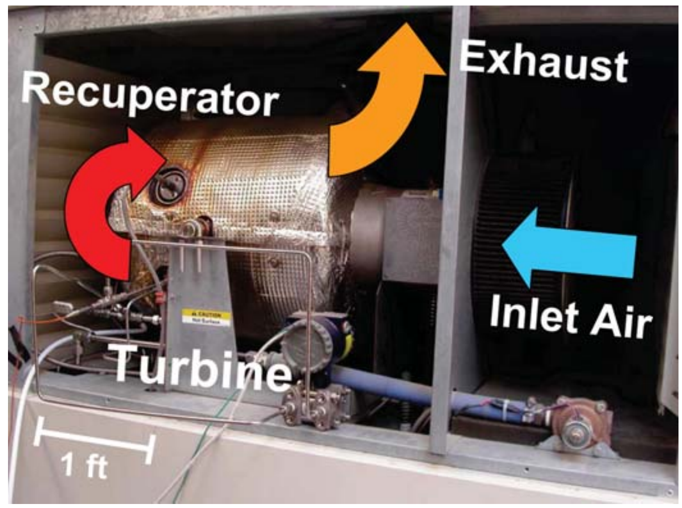

Figure 1
Capstone C30 Microturbine

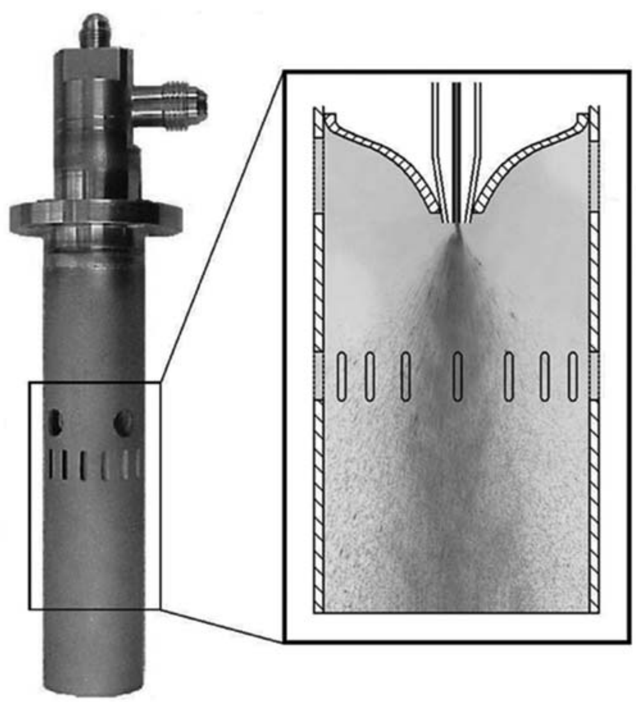

Figure 2
Capstone C30 liquid fired injector with enlarged cross-section showing fuel spray

distributing the spray by inducing a helical spin to entering air (Figure 3). Both of these air streams play an important role in the preparation of the fuel/air mixture and are therefore expected to influence the formation of pollutants during combustion. The ratio of fuel to air governs the degree of combustion heat release and, in turn, determines the fraction of pollutants formed in the exhaust products.

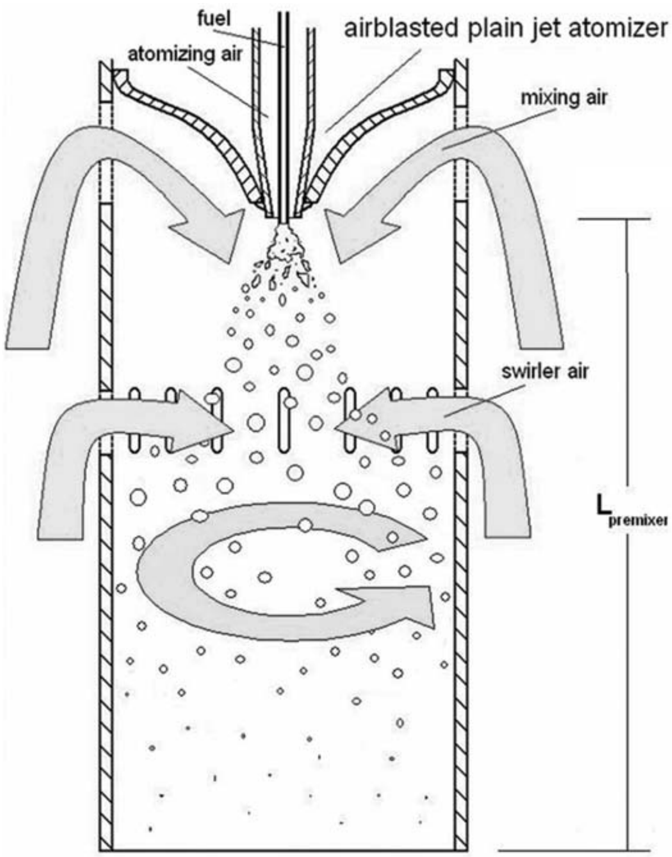

Figure 3
Capstone C30 fuel injector and spray phenomena. The arrows show the manner in which high temperature combustion air enters the injector and vaporizes, further atomizing and mixing the fuel. The premixer length, $L_{premixer}$, is defined as the injector tube length the atomized fuel droplets have to vaporize and mix with air before they ignite. The mean droplet residence time, $t_{residence}$, and evaporation time, t_{vap}, in the injector tube are the two key parameters that determine whether prevaporization is attained.

The fuel preparation process involves the atomization of liquid fuel, followed by vaporization and mixing. Air-liquid atomization is used to enhance both the production of fine droplets and mixing (Georjon and Reitz, 1999; Lefebvre, 1998). The rate of vaporization and mixing is determined largely by the amount of available energy capable of performing work (enthalpy) and the fluid dynamics of the combustion air and swirler air. This study explores the role of each step in the fuel preparation process and the subsequent emissions performance to assure that the design results in ultra low emission of air pollutants, and to identify the degree and manner in which emissions can potentially be reduced even further.

Experiment

Experiments were conducted with an MTG Test Rig, a Mixing Test Rig, and an Atomization Test Rig. Diesel Fuel #2 (DF-2) was used in all the rigs.

MTG Test Rig

Exhaust emissions were measured with a Horiba PG-250 emissions analyzer via an extractive sample probe centered at the exit plane of the exhaust stack. Emissions were characterized for 50 to 100 percent load operating conditions. The accuracy of the NO_x and CO measurements is ± 0.25 parts per million volume dry (ppmvd) and ± 2 ppmvd, respectively. The PG-250 was spanned and zeroed before each measurement and the span was verified at the end of each test run. A special injector was fabricated to allow the connection of pressure transducers and thermocouplers near the air-blast nozzle exit of the injector during operation.

Two sets of injectors were used in the MTG to study the effect of the fuel-air ratio on emissions (Figure 4). Because NO_x and CO emissions are a function of temperature, it is important to assess the sensitivity of the emissions to the reaction temperature. The increase in hole size is based on an anticipated reduction of NO_x associated with lower temperatures produced by reducing the injector fuel-air ratio.

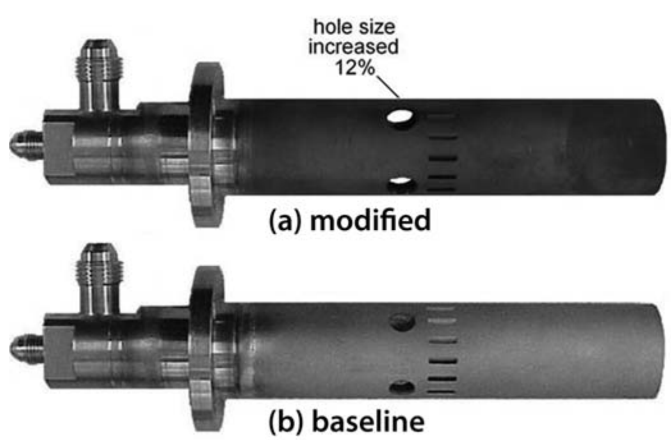

Figure 4
Baseline and modified C30 injectors

Mixing Test Rig

The mixing test rig, a full-scale 1/3 section of the C30 engine, simulates the air flow characteristics in the engine (Figure 5). The design of this test rig was developed and verified by engine measurements and computational fluid dynamics (CFD) analysis using CFD-ACE+ software.

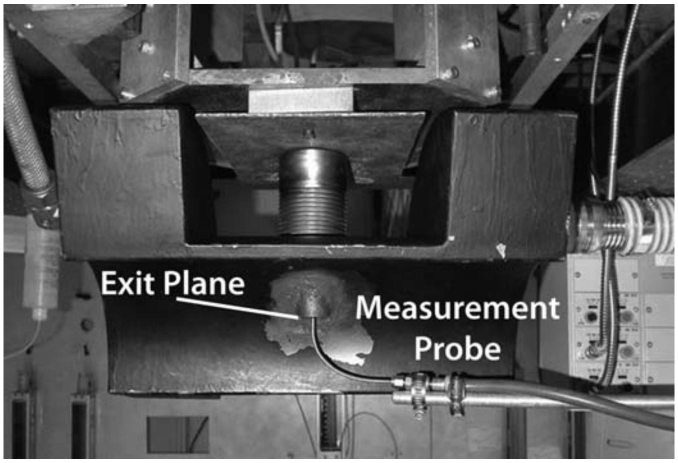

Figure 5
Single injector mixing test rig with hydrocarbon measurement probe

Gaseous methane was used as fuel in a computer aided model of the Capstone injector and surrounding flow geometry, which is shown in Figure 6. The inlet conditions for the air entering the annulus shown in Figure 6 were determined by measurements made in the MTG test stand, and verified the fully developed flow assumption used in the model. The fuel inlet condition was set as a constant mass flow at the injector centerline. The outlet of the geometry was set to constant pressure.

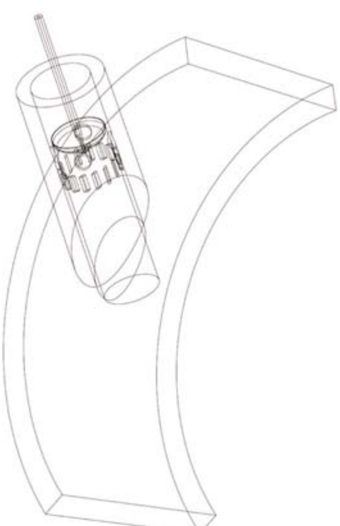

Figure 6
CFD geometry of C30 injector and surrounding flow path; shown with downward orientation and with air flow entering along far right side of arc

In the mixing test rig configuration, a Horiba FIA-236 hydrocarbon analyzer (flame ionization detector) was used to map fuel concentration over the exit plane of the injector. Rather than using liquid fuel for these tests, natural gas was flowed through the fuel line. Natural gas was used as a trace in the air flow to identify the air's role in mixing. Results obtained with this test rig allowed mixing performance of different injector configurations and/or operating conditions to be quantitatively compared.

Atomization Test Rig

The single injector test rig was designed to characterize C30 injector atomization performance. Tests were conducted on the fuel injector atomization independent of the fuel-air premixer tube (Figure 7).

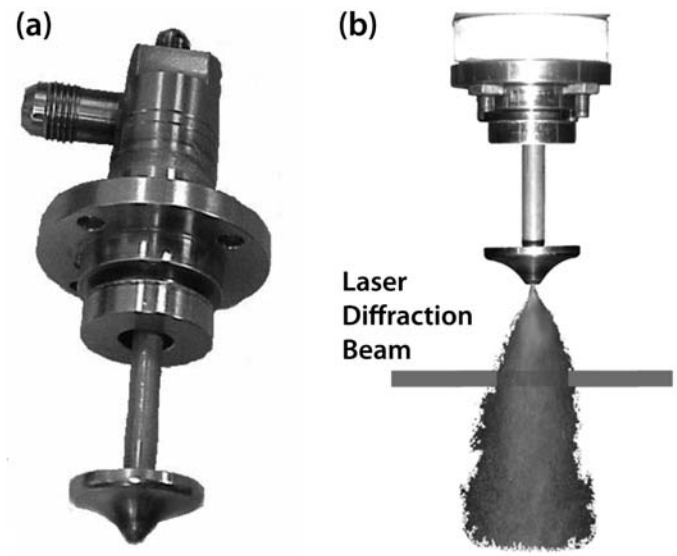

Figure 7
(a) Injector without premixer tube and (b) injector in test configuration

The premixer was removed from the setup to isolate the role of the air-blast on the atomizer performance (Figure 7a). A Malvern laser diffraction system with a 100 mm focal length lens was used to measure and quantify the characteristics of the fuel spray (Figure 7b). A calibration reticule (Laser Electro-Device Ltd Model RR-50.0-2.0-0.030) was used, and measurements of the spray were taken at one injector tube diameter (2.67 cm) from the injector exit plane. Further traversing of the flow was performed to ensure measured spray characteristics remained invariant throughout and a representation of the overall flow was established.

Results and Discussion

Emissions

Emission measurements were obtained for the C30 MTG operated on DF-2 with both sets of injectors. Results versus load setting are presented for the baseline injector as the open points in Figures 8 and 9 for NO_x and CO emissions, respectively. The results are presented as corrected to a constant level of O_2 (15%) to ensure that differences in the amount of air in the exhaust stream is not simply diluting the concentration of pollutants. For the baseline injectors, CO emissions decrease with load and are below 10 ppmvd corrected at 15% O_2 for 50–100% load operation. NO_x emissions increase with load and are approximately 20 ppmvd at 15% O_2 at maximum power output. The results demonstrate that the MTG produces orders of magnitude less NO_x than the current reciprocating backup generation devices.

Results are also presented for the modified injector, shown as filled symbols in Figures 8 and 9. The results for the modified injector are higher than those produced by the baseline, yet are still low compared to those produced by a typical reciprocating engine. The modified MTG produces about 2 g of NO_x and CO per kilowatt hour (kW-hr) at full load, compared to modern reciprocating diesel generators that easily produce 20 g of NO_x and CO per kW-hr (Miller, 2004).

For both injectors, the NO_x and CO emissions levels were below 30 ppm for all loads studied. This illustrates that, even with a significant modification in combustion conditions (by decreasing the equivalence ratio by 12%), the MTG still demonstrates superb emissions performance when compared with the 1000+ ppm emissions of the reciprocating engines currently in use as backup generators.

The results also suggest that the fuel-air mixture produced by the injectors is not fully premixed and prevaporized. If the fuel and air were ideally mixed, the larger air holes in the modified injectors would result in reduced reaction temperatures and, therefore, reduced NO_x emissions. To illustrate, the expected behavior with assumed premixed/prevaporized operation is represented by the NO_x and CO trend lines derived from MTG measurements (Figure 10). Since the actual NO_x emissions increased with more injector air flow, it can be concluded that the assumption of premixed/prevaporized is not valid.

Mixing Performance

Ideal premixed/prevaporized conditions were not attained; therefore, the level of premixing achieved is of interest. To help establish the degree to which the injectors were performing, the baseline emissions measurements were compared to results determined for a near perfect, prevaporized and premixed combustion system (Figure 11) (Leonard and Stegmaier, 1994). This comparison presents NO_x as a function of average reaction temperature for the baseline results

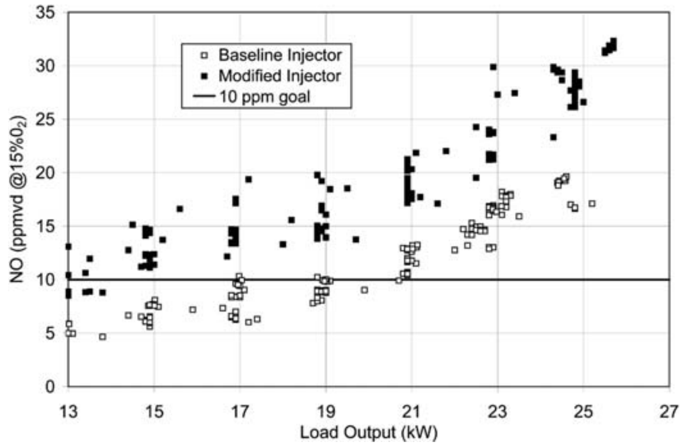

Figure 8

NO_x emissions versus load with modified injector

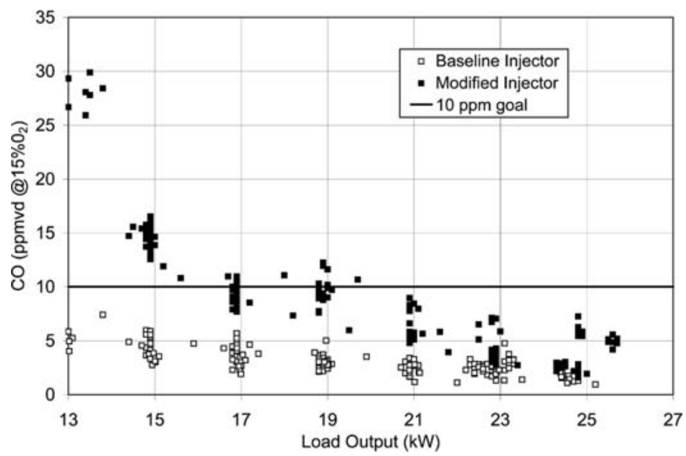

Figure 9

CO emissions versus load with modified injector

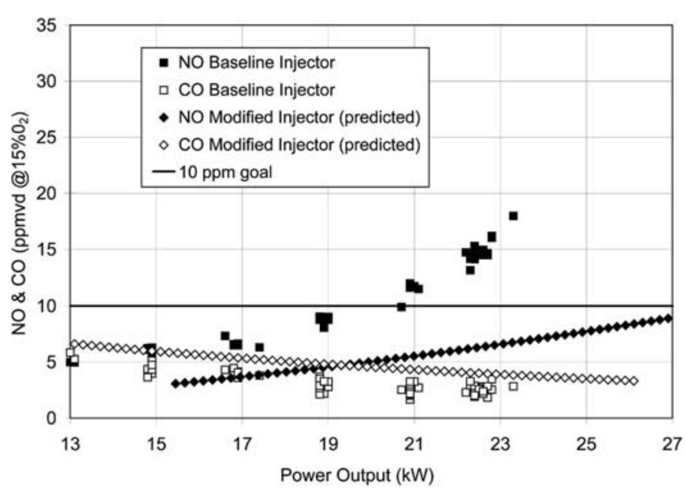

Figure 10

Expected NO_x and CO behavior for two injectors assuming ideal prevaporization and premixing

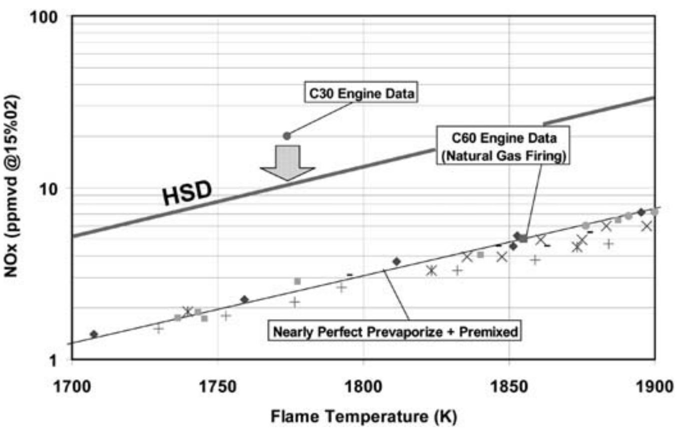

Figure 11
Effects of nonuniform fuel and air mixing on NO_x formation

along with the generalized data obtained from previous measured emissions using high sulfur diesel (HSD) and natural gas. The HSD line represents a theoretical NO_x limit for a heavier distillate diesel fuel compared to DF-2 with perfect premixing and is used as a worst case scenario in terms of emissions (Lee et al., 2001). According to the results, it appears that mixing in the C30 liquid fuel injector can be improved (Figure 11). Note that emission results for a natural gas fired at 60 kW MTG operating at similar conditions and with a similar fuel injection approach is able to achieve excellent premixing (Phi et al., 2004). By plotting these results (Figure 11), its position on the line affirms the opportunity to improve mixing. As a result, an opportunity to improve the emissions performance through an improvement in the premixing of the injector is apparent.

The modified injector showed increased NO_x emissions, meaning that either the atomization or mixing performance of the modified injector was inferior to that of the baseline. Any NO_x reductions potentially achieved by reducing the average fuel/air ratio are offset by inferior mixing.

To further assess the mixing characteristics of each injector, tests were conducted at atmospheric conditions using the single injector mixing test rig. Natural gas was flowed through the liquid fuel passage as fuel and a flame ionization detector (FID) based hydrocarbon analyzer was used to map the injector exit mixing profile by measuring the methane concentration at discrete grid positions at the injector exit plane.

The single injector mixing measurements were carried out for both the baseline and modified injectors. The pressure drop of the engine was used to scale the fuel and total air flow rates for atmospheric conditions. Normalized concentration profiles derived from the experiments are presented

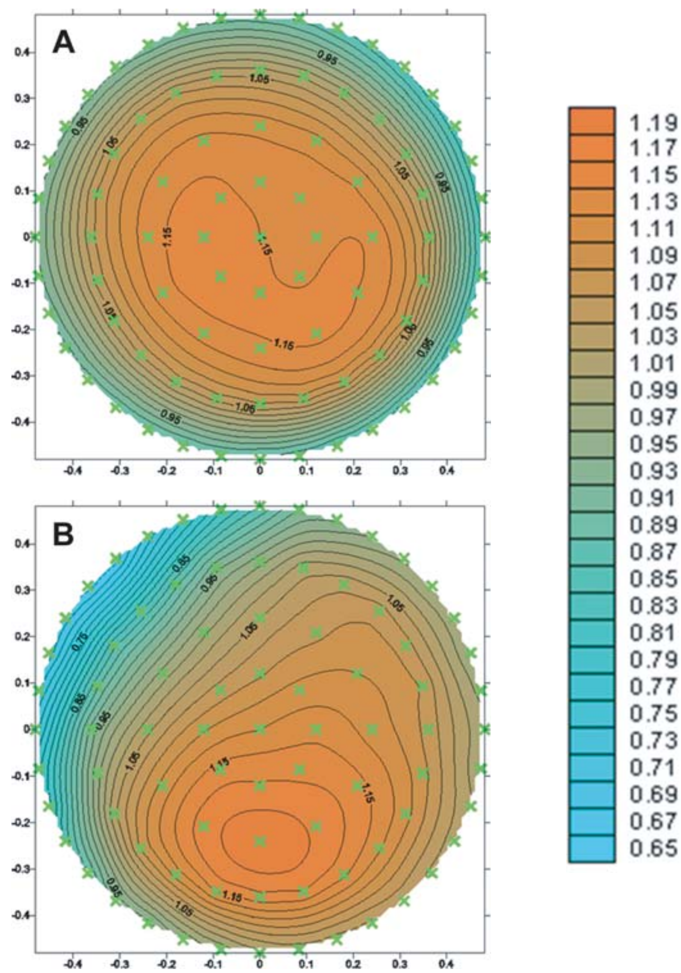

Figure 12
Normalized exit plane concentration profiles: (A) Baseline injector, (B) Modified injector

in Figure 12 with orange being higher methane concentration. To quantify this variation, the coefficient of variation of the exit plane fuel/air ratio was calculated as 11.6% and 13.6% for the baseline and modified injectors, respectively. The results show that variation in mixing is 20% higher than the baseline. This helps verify and quantify the inferior mixing performance of the modified injector. Variation in the degree of mixing would lead to regions of higher local temperatures and, therefore, higher NO_x emissions.

A computational fluid dynamic (CFD) model[1] was developed to further assess the mixing performance of the fuel injectors. The assumptions for this model were those explained earlier in the experiments-mixing test rig section of this paper. The results show that, by enlarging the air hole size and maintaining system flow conditions, addition-

1. CFD-Ace+ (ESI) was used to compute the flowfield and mixing. A Reynolds Averaged Navier Stokes (RANS) approach was used, with standard k-e turbulence model, and a turbulent Schmidt number of 0.5 (Qing, 2005).

al mixing interactions with fuel are required for optimal premixing. Therefore, in agreement with the experimental mixing rig results, a less uniform concentration of fuel and air is produced at the injector exit plane when compared to the baseline injector (Phi et al., 2004).

It is also possible that the mixing is impacting CO emissions by cooling the reaction in the relatively fuel lean region near the injector wall in the upper left portion of Figure 12b. The inferior fuel distribution seems to be more directly associated with the enlarged holes, but a slight misalignment of the fuel tube within the atomizing air passage may have some impact on fuel distribution. However, testing different injectors of the same type with different alignments has shown to produce repeatable mixture distributions and emissions.

Measurement Results with Instrumented Injector

Although the mixing tests suggest significant differences in the performance of the two injectors, the tests were conducted with natural gas, resulting in near instantaneous vaporization. In a normal engine, liquid—not natural gas—is injected. As a result, further analyses of the role of atomization and vaporization were carried out.

Atomization tests were conducted under standard conditions. Since these conditions differ from the elevated temperatures and pressures inside the engine, the operation of the injector had to be scaled to match the key parameters that control atomization. Injector conditions during engine operation were measured to establish the scaling. In air-blast atomization, pressure, not temperature, plays the dominant role in determining droplet formation and overall spray behavior. Therefore, atomization studies can be performed at atmospheric conditions by matching pressure drops in the nozzle. Table 1 shows the associated MTG pressures and pressure drops for full power conditions. Equation 1 defines the pressure drop of combustion and atomization airflows. The pressure drop of the combustion airflow is determined from the calculated total mass flow of the C30 and the measured injector area.

Table 1
Air flow pressure drops in MTG

Pressure of combustor	0.335 MPa
Pressure drop of combustion air flow	5.6 %
Pressure of atomization air inlet	0.344 MPa
Pressure drop atomization air flow	2.6 %

$$\textit{pressure drop } \Delta P(\%) = \frac{\textit{pressure drop}}{\textit{pressure of combustor}} \times 100 \qquad (1)$$

Atomization and Evaporation Study

Measurements of the mean fuel drop size (Sauter mean diameter) produced by the airblasted plain jet atomizer for the baseline injector were obtained using laser diffraction under scaled engine conditions using DF-2. All of the experimental data were obtained using air supplied via an air-compressor at standard conditions. Test conditions were derived as follows:

1. Determine combustion air flow using the pressure drop that was obtained from engine measurement as a scaling parameter.
2. Calculate fuel flow rate matching fuel to combustion air ratio at the maximum load.
3. Determine atomization flow using the pressure drop that was obtained from engine measurement.

Atomization air varied such that the atomization air to liquid mass flow ratio (ALR) spanned from 0.2 to 0.7. The results are plotted as the Sauter Mean Diameter (SMD) versus ALR and as in Figure 13 along with a comparison of an empirical expression (Equation 2) that was developed to describe drop sizes for a similar fuel injector design (Rizk and Lefebvre, 1984).

In Equation 2, D_{32} is the Sauter Mean Diameter, d_o is the liquid discharge opening diameter, σ is the liquid surface tension, U_R is the relative coflowing velocity of the two streams, ρ_A is density of air, ρ_L is the liquid density, and μ_L is the liq-

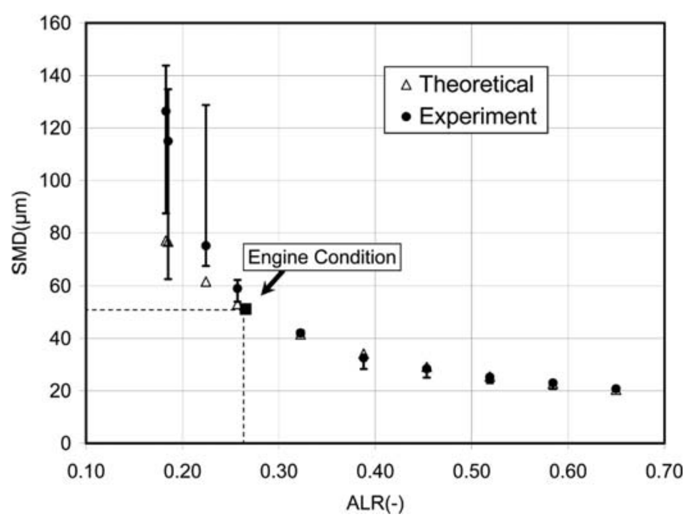

Figure 13
Influence of ALR on SMD from calculation using Equation 2 and measured values using laser diffraction

$$\frac{D_{32}}{d_o} = 0.48\left(\frac{\sigma}{\rho_A U_R^2 d_o}\right)^{0.4}\left(1+\frac{1}{ALR}\right)^{0.4} + 0.15\left(\frac{\mu_L^2}{\sigma \rho_L d_o}\right)^{0.5}\left(1+\frac{1}{ALR}\right) \qquad (2)$$

uid viscosity. The error bars illustrate the lack of achievement of stable atomization, which is undesired since the presence of large droplets causes variations in local equivalence ratio and, therefore, emissions. Given that Equation 2 was derived for ALRs between 2 and 8, finding good agreement between the equation and the experimental data for ALRs as low as 0.30 provides a validation for the expansion of the range of ALRs in which Equation 2 can be applied.

Based on the agreement of Equation 2 to the experimental data shown in Figure 13, it is reasonable to apply Equation 2 to estimate the atomizer's performance at actual engine conditions. If Equation 2 is applied using the properties at actual engine conditions, the D_{32} at full load is estimated to be 50 µm. Equation 2 can also be used to explore how to alter the injector operation to change the droplet sizes produced. The insight from using the above equation for the C30 atomizer is illustrated in Figure 14.

If the evaporation rate is insufficient, liquid fuel enters the primary zone, potentially contributing to higher NO_x emissions. Subsequently, an analysis of the vaporization characteristics was carried out to explore whether the atomization quality is sufficient to lead to full prevaporization.

The analysis was performed using an "effective evaporation constant", λ_{eff} (Lefebvre, 1998). This concept simplified calculations of the evaporation characteristics of fuel droplets by allowing the determination of λ_{eff} algebraically from flow properties and operating conditions, and avoids solving systems of nonlinear partial differential equations. The average droplet lifetime was determined by the D^2 Law with the adaptation of a modified evaporation constant, λ_{eff}, where D_0 is the initial drop size, which is equal to the SMD in this case, λ_{eff} is the effective evaporation constant, and t_e is the evaporation time (Equation 3).

$$t_e = \frac{D_0^{\,2}}{\lambda_{eff}} \quad (3)$$

Figure 15 shows the results of this analysis in the context of C30 emissions and suggests that droplet lifetime is greater than residence time within the C30 injector. This indicates that droplets will persist in the combustor, which is not desired for low emissions. This could show why measured emissions are well above the levels associated with well-premixed systems (Figure 11).

The role of the air flowing through the combustion air holes on atomization also needs to be considered. While it is expected that the atomizing air is the primary flow used in air-blast atomization of the liquid fuel, the interaction of the combustion air jets with the spray droplets also plays a role. By computing the Weber Number—the ratio of inertial to liquid surface tension forces (Equation 4)—for the atomization and combustion air at full operating load, it is found that the atomization air plays a dominant role in fuel breakup.

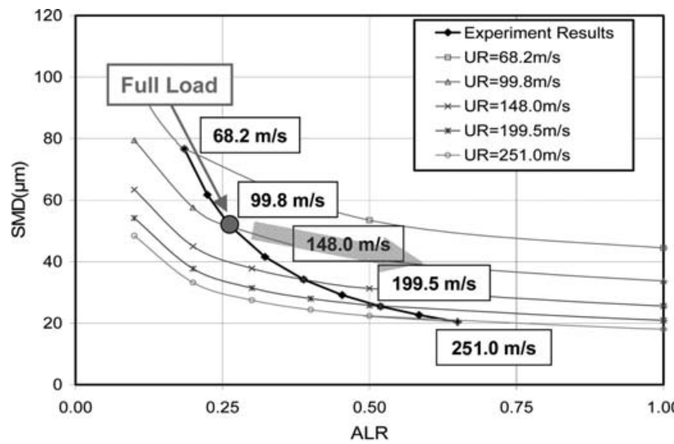

Figure 14
ALR and UR effect on SMD for C30 airblast atomizer. The arrow illustrates finer drop sizes at full load condition.

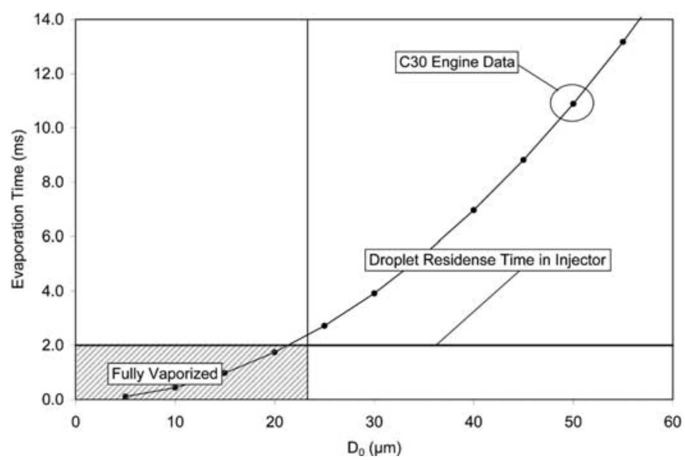

Figure 15
Effect of SMD on drop lifetime

In Equation 4, ρ_A is the density of air, U_R is the relative velocity of the coflowing streams, D_{32} is the Sauter Mean Diameter, and σ is the liquid surface tension. It is assumed that the combustion air flows parallel with DF-2 at the nozzle exit.

$$We = \frac{\rho_A U_R^{\,2} D_{32}}{\sigma} \quad (4)$$

Based on the Weber numbers, shown in Table 2, the combustion air aids atomization. Since the modified injector has a lower Weber number, larger droplet sizes (and therefore longer vaporization times) are a significant factor in the increase in NO_x emissions observed for the modified injector.

Table 2
Weber numbers for baseline and modified injectors using 50 micron SMD

	Atomization Air	Combustion Air
Baseline	30	7.6
Modified	30	5.8

Conclusion

NO_x and CO emissions for a commercial Capstone C30 liquid fuel fired microturbine generator have been characterized. The sensitivity of the emissions performance to load, combustor fuel to air ratio, atomization of the liquid fuel, fuel and air mixing, and reaction temperature were established.

The results affirm the ability of a gas turbine engine to achieve low emissions of both NO_x and CO. The engine has superior emissions performance compared to reciprocating engine technology currently being used for backup power.

The research also clarifies the distinction between emissions reduction strategies for a liquid fueled versus a well-premixed gasous fueled turbine engine, and demonstrates that air pollutant emissions can be further reduced. While increasing the airflow to the injector can, in a simplified model, reduce reaction temperatures and NO_x emissions, the observed increase in emissions indicates that the key assumptions of complete vaporization and perfect mixing behind this model do not hold. This result is significant in that it indicates that the reasonable and intuitive approach of improving the emissions by simply reducing the injector equivalence ratio and ensuring sufficient mixing do not apply in the current system. This is attributed to the complexity of the phenomena involved in the preparation of the fuel and air prior to combustion (i.e., atomization, vaporization, and mixing). Measured mixing performance of the two injectors reveals that NO_x correlates with injector mixing performance. As a result, strategies that further improve fuel-air mixing while maintaining a reasonable level of atomization can potentially reduce emissions further.

Acknowledgements

A special thanks is due to my research advisors, Professor Scott Samuelsen and Dr. Vince McDonell, whose unique insight, guidance and encouragement have contributed to the research presented herein. I would also like to acknowledge Josh Mauzey of the UCI Combustion Laboratory and Sosuke Nakamura of Mitsubishi Heavy Industries, whose patience, persistence, and professional experience has provided insight and perspective to the research. I would like to acknowledge the California Energy Commission (Contract 500-00-020) and Capstone Turbine Corporation for their funding and support. Finally, I would like to thank my family for their unconditional love and support.

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