Effect of Water Injection into Aero-derivative Gas Turbine Combustors on NOx Reduction

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***Abstract* — Oxides of Nitrogen (NOx) generated from gas turbines causes enormous harm to human health and the environment. As a result, different methods have been employed to reduce NOx produced from gas turbine combustion process. One of such technique is the injection of water or steam into the combustion chamber to reduce the flame temperature. A twin shaft aero-derivative gas turbine was modelled and simulated using GASTURB simulation software. The engine was modelled after the GE LM2500 class of gas turbine engines. Water injection into the gas turbine combustor was simulated by implanting water-to-fuel ratios of 0 to 0.8, in an increasing order of 0.2. The results show that when water-to-fuel ratio was increased, the Nox severity index reduced. While heat rate and fuel flow increased with water-to-fuel ratio (injection flow rate).**

***Index Terms* — Flame Temperature, Fuel Flow, Heat Rate, NOx Severity Index, Water-to-Fuel Ratio.**

I. Introduction

With the growing concern about the impact of emissions generated from gas turbine combustion on human health and the environment, coupled with stringent regulations regarding emissions generated, there is the need to reduce the amount of emissions (with specific emphasis on Nox generated) arising from gas turbine combustion. Gas turbines operated under high power setting generate large amount of NOx which affects the environment as well as human health. As a result, different methods have been used in the past, to reduce NOx emission generated from gas turbine combustion processes. Lefebvre and Ballal [1] stated that the easiest means of NOx reduction in gas turbines was to use water/steam to lower the combustion flame temperature. The reduction of Nox through water injection is achieved by reducing the formation of oxygen radical, which is the main factor responsible for the NOx production [2]. Lefebvre and Ballal [1] stated that NOx emission can be reduced by lowering the combustion zone temperature since NOx formation is exponentially dependent on temperature.

Urbach et al. [3] designed an automated system to control the water injected into the combustor. It was reported that the automated control system compensated for changes in humidity, load, and temperature. Hence, it was stated the system was effective for controlling NOx emissions. Galdo et al. [4] demonstrated that 80% NOx reduction was achievable in a diesel engine through the injection ammonia. The authors further add that effectiveness of NOx reduction using ammonia injection depends on the timing, and that optimum Nox reduction was achieved when ammonia was injected during the expansion stroke. Water injection within the combustor of a turbojet was investigated to ascertain its benefits and drawback [5]. A test campaign on the turbojet was conducted in conjunction with numerical simulation of the combustion process where three dimensional CFD code was used. Reductions in nitrogen oxide were quantified in the study of Novelo and Igie [6] using correlations derived from engine emission data. An integrated performance-CFD chemical reactor methodology was developed to investigate the effect of steam addition on Nox emissions for Jet-A fuel in an aircraft combustor [7]. Farokhipour et al. [8] investigated the process of spray water injected into gas turbine combustors by implementing the Eulerian-Lagrangian model. The effect of different injection parameters, namely injection position, direction and mass flow rate were investigated using an Eulerian-Lagrangian model created, to ascertain their influence on performance and emission generated from a gas turbine combustor at different swirl numbers [8]. Gonca [9] investigated the application of steam injection on diesel engine fueled with ethanol-diesel blend. The author reported that the significant improvement in performance and considerable reduction in Nox emissions were achieved when steam was injected into the engine. Kollrack and Aceto [10] stated the rate of NOx produced in gas turbines is reduced by adding liquid water in quantities equivalent to the fuel consumed by the engine. Kollrack and Aceto [10] employed a numerical program which has the capability to simultaneously solve time dependent concentration, thermodynamic and gas dynamic equations, to analyze the addition of liquid water into gas turbine combustor so as to achieve reduced levels of NOx production. From literature search conducted, it is obvious that there has never been any detailed study which analyses the effect of water injection on NOx reduction and the overall performance of the gas turbine. This study analyses the effect of water injection into the combustion chamber on NOx reduction and the overall gas turbine performance.

II. Materials and Methods

GASTURB software was employed to model and simulate the effect of water injection in the gas turbine combustor. The modelled aero-derivative twin shaft gas turbine was derived from GE LM2500 class of gas turbine. The modeled engine was achieved by selecting a twin shaft engine configuration from the software interface and consequently implanting the design specification data obtained from open domain, which are similar to the proposed engine model. Few of the data such as component

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efficiencies and turbine entry temperature were adjusted to arrive at the expected design engine specifications. The simulations of the water injection into the combustor on the overall performance of the gas turbine were carried out with the default natural gas fuel provided in the software. Fig. 1 shows schematic layout of the twin shaft aero-derivative gas turbine engine adopted for the investigations, while Table 1 presents the design point performance specifications.

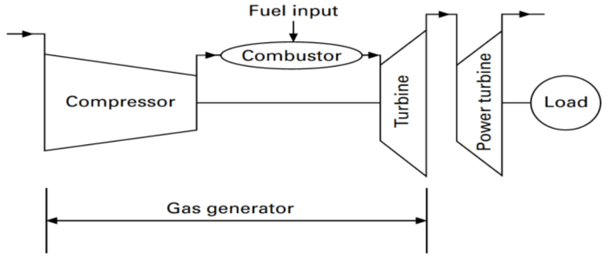

Fig. 1. Industrial gas turbine engine layout.

TABLE I: ENGINE DESIGN SPECIFICATIONS (COURTESY OF GENERAL ELECTRIC)

Parameter	Value
Power Output (MW)	25
Thermal Efficiency	36
Exhaust Flow Rate (kg/s)	70.5
Exhaust Temperature	839K
Heat Rate	9705kJ/kWh
Pressure Ratio	12.38

The rate of Nox emissions controlled is directly influenced by the quantity of water (water-to-fuel ratio) injected into the gas turbine combustor. However, it is imperative limit the water-to-fuel ratio (quantity of water injected) in order not to generate other forms of emissions arising from products of incomplete combustion such as carbon monoxide (CO) and Unburned hydrocarbon (UHC). According to Syed [2] that water injected should be as low as possible while still meeting the emission requirements. This is because as more water is added to reduce NOx produced, so the carbon monoxide and unburned hydrocarbons produced in combustion process increase. Major [11] stated that water-to-fuel ratio in the range of 0.6-0.8 generally results in little or no increase in carbon monoxide and unburned hydrocarbons produced. However, the author stated the emissions rates of carbon monoxide and unburned hydrocarbons produced are on exponential rise when water-to-fuel ratio exceeds 0.8 [11]. Similarly, water-to-fuel ratios varying from 0.15 at near idle condition to 0.88 under full throttle were considered as optimum (Courtesy General Electric). Based on the above, the range of water-to-fuel ratios considered in this study is from 0 to 0.8. In addition, the simulations of water injection into the gas turbine combustor to reduce the flame temperature were conducted under constant load condition. The simulations were conducted at constant load conditions because according Lefebvre and Ballal [1] water and steam injection are effective means of reducing Nox for stationery gas turbines operated at near constant load conditions.

Fig. 2 shows the implanted water injection (water-to-fuel ratio) simulations on the GasTurb interface.

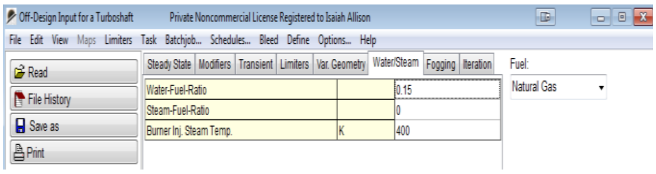

Fig. 2. Water injection simulation interface.

III. RESULTS AND DISCUSSION

Fig. 3 shows the plot of NOx severity index against water-to-fuel ratio. As can be seen from the figure, when the water-to-fuel ratio is increased from 0 to 0.8, the NOx severity index reduced from 0.4759 to 0.4615, which is approximately 3% reduction. This reduction in NOx severity index can be attributed to increased rate of water injected into the combustor, which acts a heat sink, thereby causing the combustion flame temperature to reduce, which in turn reduces the NOx produced.

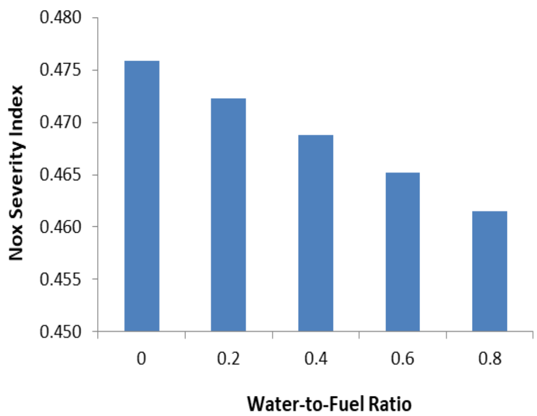

Fig. 3. Nox severity index against water-to-fuel ratio.

Fig. 4 shows the plot of fuel flow against water-to-fuel ratio. From the figure, it is obvious that fuel flow increased with water-to-fuel ratio. When water-to-fuel ratio was increased from 0 to 0.8, the fuel flow increased from 1.4129kg/s to 1.4504kg/s. This signifies that when water is injected into the combustor, more fuel is required to heat the water to combustion temperature. In addition, the consumption of addition fuel to heat the water to combustion temperature causes the thermal efficiency to reduce. These findings agree with the study of Syed [2].

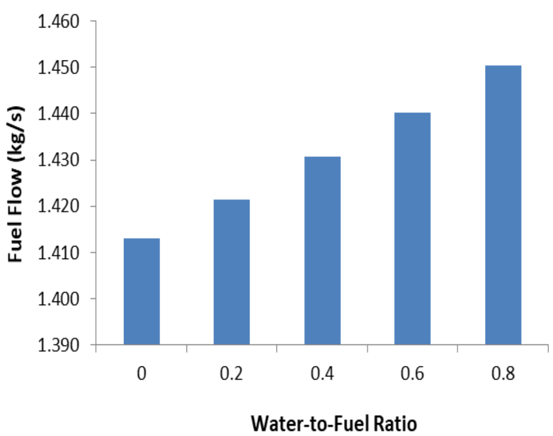

Fig. 4. Fuel flow against water-to-fuel ratio.

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Heat rate is plotted against water-to-fuel ratio in Figure 5. The figure shows that heat rate increased with water-to-fuel. When water-to-fuel ratio was increased from 0 to 0.8, the plots show that the heat rate increased from 9923 kJ/kWh to 10187 kJ/kWh, which is about 2.6%. The increased heat rate with water injection signifies increased heat input for a given work done. Also, increased heat rate with water addition into the combustor would result in reduced thermal efficiency. These findings agree with the study of Staudt [12] where it was reported that water injection into the combustor causes the heat rate to increase by 2-4%.

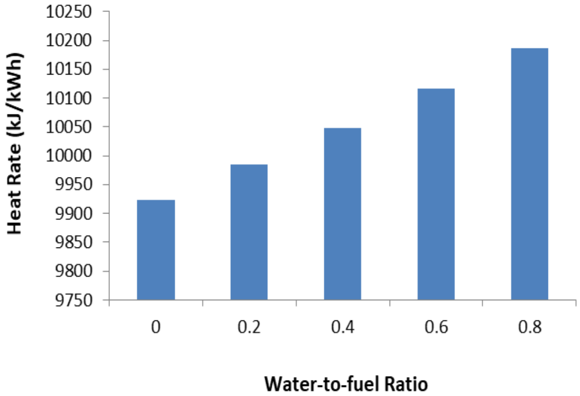

Figure 5: Heat Rate against water-to-fuel ratio.

IV. Conclusion

This study presents the analysis of water injection effect on Nox reduction and the overall performance of the gas turbine engine. A twin shaft aero-derivative gas turbine was modelled and simulated using GASTURB simulation software. Water injection into the gas turbine combustor was simulated by implanting water-to-fuel ratios from 0 to 0.8, in an increasing order of 0.2.

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