FUNDAMENTAL IMPACT OF FIRING SYNGAS IN GAS TURBINES

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INTRODUCTION

The move towards the reduced greenhouse gas emissions with the use of synthetic gas (syngas) as a fuel for the production of electricity is predicted to grow sharply in the near future as a result of:

- global warming and ocean surface acidification, which imply the need to control and reduce greenhouse gas emissions.
- the low estimated reserves of oil; and
- rising cost as well as demand for natural gas and the need to reduce the dependence on fossil fuel imports from unstable areas.

The integrated gasification combined cycle (IGCC) produces electricity from a solid or liquid fuel. The fuel is first converted to syngas which is a mixture of hydrogen and carbon monoxide. The syngas is then converted to electricity in a combined cycle power block which consists of a gas turbine process and a steam turbine process with heat recovery generator (HRSG)

The gas turbine when fully fired on typical syngas compositions has the potential to develop enhanced power output capacity due in large part to the significant flow rate increase ($\approx$ 14% increase over natural gas), resulting from the low heating value fuel combustion products passing through the turbine. This power output could increase as much as 20-25% when compared with the natural gas. The mechanical capability of a specific turbine and its surge margin requirement limit this capability differently for each machine, setting a specific maximum output. However, this increase in power output is also accompanied by an increase in the moisture content of the combustion products due largely to higher hydrogen content in the syngas and the increased turbine flow which can contribute significantly to the overheating of turbine component parts. Most OEMs therefore recommend a reduction in firing temperatures to maintain hot gas path parts at temperatures similar to that of natural gas. The reduction criteria are different across each OEM and it has been difficult to understand fully the reasons behind the selected criteria.

The aims of this work therefore are to analyze the fundamental impacts of firing syngas in combustion turbines and indicate the appropriate amount of reduction in firing temperature needed to maintain the same hot section metal temperatures as experienced with natural gas firing. It is believed that studying the fundamental impacts may bring to light ways to mitigate the negative impacts of syngas firing. It will also prepare new engineers and scientists for work at gas turbine OEMs where this issue will be of high importance in the coming years.

GATECYCLE MODELING DETAILS

The modeling of a typical Integrated Gasification Combined Cycle (IGCC) power plant was done using the GateCycle software developed by GE Enter software, which is fully owned by the General Electric Power Systems. The software predicts the design as well as the off-design performance of combined cycles and fossil boiler power plants, cogeneration systems, advanced gas turbine cycles and many other energy systems and it is also used for quick assessments, detailed engineering, design, retrofitting, repowering and acceptance testing applications [1]. The software's component-by-component approach, together with its advanced macro capabilities, enables modeling of virtually any type of systems.

Design point (baseline model)

For the purpose of this study, a baseline case plant was established using technology, which could be used to compare the scheme under consideration. Also, certain parameters which allow comparison of the other cases on consistent bases were established. The Siemens SGT6-5000F (formerly known as W501F) class gas turbine (Fig.1) was used as expander and natural gas as a baseline fuel. Engine parameters were matched with the ones from the Siemens Plant Performance Estimation Program (SIPEP). Basic engineering design parameters which are common to all the cases tested are;

Ambient conditions;	
Design temperature	59 ^{o}F
Design pressure	14.70 psia
Design relative humidity	60%
Exhaust pressure	15.0 psia

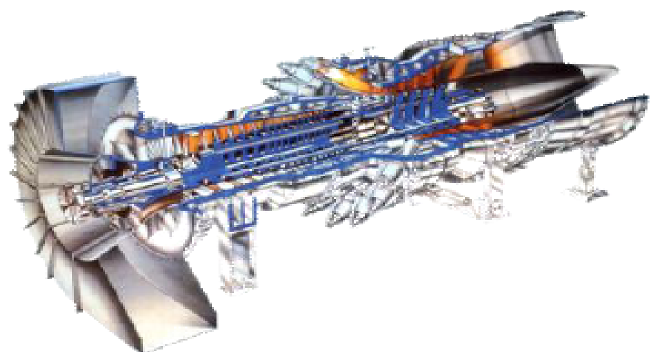


Figure1. Siemens SGT6-5000F gas turbine

In order to satisfy both the mass continuity and energy balance, the components were aerodynamically coupled along the flow and cooling paths; and mechanically coupled by shafts according to the engine configuration. The SIPEP results were matched by adjusting the turbine sections efficiencies to match power, heat rate and exhaust temperature.

This design case was used to calculate the corresponding nozzle areas of the turbine sections as well as the appropriate pressure ratio, efficiency and flow rate. The baseline case has a net power output of 195.6 MW and an efficiency of 37.2 percent at the design point (Ambient temperature is 59^{o}F). The block diagram of flow model for the design case is shown in Fig. 2 below.

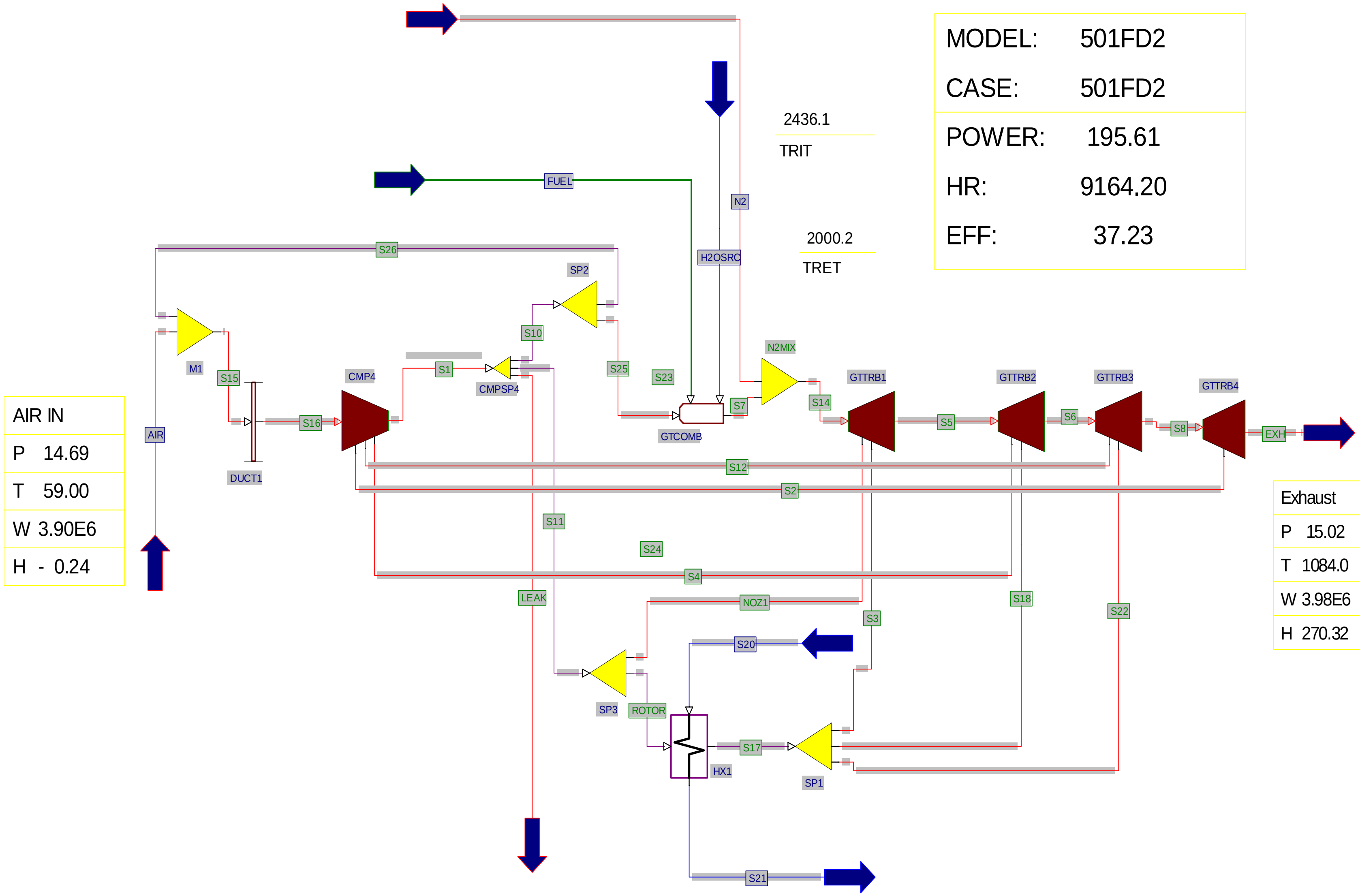


Figure 2. Block diagram showing design conditions for natural gas

For the design case, the total cooling flow entering the nozzles or rotors is split up along the length of the expander as a constant fraction of the inlet flow to the turbine.

$$(W_{cool} = \text{fraction} * W_{inlet})$$

The cooling flow is usually more heavily weighted to the first and second stages of the expander, where the metal temperatures are higher. The calculated values are saved in the design case to be used as reference values in off-design runs. Calculated values of cooling flow to sections of the turbine are shown in Table 1.

Table 1: Cooling air flow

Section/Stage	1st	2nd	3rd	4th
Rotor cooling (Ib/hr)	186300	80217	24123	39451
Nozzle cooling (IBM/hr)	290639	66000	40000	0.00

Syngas model

Slight modifications were made to the gas turbine when it is fired with syngas based on the above discussed factors. For example, 1.0 nozzle area performance factor was used for the natural gas case, while a 1.20 area performance factor was used for the syngas model in other to accommodate the increased mass flow through the nozzle. In GateCycle, these performance factors are applied to the user inputs for design runs and to calculate parameters for off-design runs.

FUEL COMPOSITION

Gas turbines are designed primarily to be fueled with natural gas and supplying them with syngas (i.e., a fuel gas synthesized via coal gasification process) presents certain challenges that must be addressed. There are substantial differences between the chemical compositions and heating values of natural gas and syngas. Natural gas is predominantly methane, which typically comprises over 93% of its volume, with much smaller quantities of slightly heavier hydrocarbons such as ethane and butane. Its volumetric lower heating value is around 950 Btu per cubic foot.

Syngas is primarily composed of carbon monoxide and hydrogen, but also contains a significant fraction (up to 50%) of non-combustibles, such as steam, carbon dioxide and nitrogen. Carbon monoxide and hydrogen has a lower heating value of about 320 Btu per cubic foot, or about 1/3 the lower heating value of methane (natural gas). When combined with nitrogen and water in the gas stream, the fuel gas has an overall Btu value of about 120 Btu per cubic foot. The dilution of the fuel with nitrogen and water (syngas saturation) reduces NOx emissions by reducing the peak flame temperatures. The three syngas fuels used for this study with their compositions are shown in Table 2.

Table 2: Gas fuel specification

Component	Primary Design Case	Fuel A (mol.)	Fuel B (mol.)	Fuel C (mol.)
H_2	0.0000	0.1214	0.1861	0.3998
O_2	0.0000	0.0009	0.0000	0.0000
CH_4	1.0000	0.0005	0.0013	0.0014
CO	0.0000	0.2503	0.1952	0.0092
CO_2	0.0000	0.0012	0.0890	0.0292
N_2	0.0000	0.5042	0.3995	0.4744
SO_2	0.0000	0.0000	0.0000	0.0000
Ar	0.0000	0.0047	0.0058	0.0061
H_2S	0.0000	1.286E-05	0.0000	0.0000
COS	0.0000	9.171E-06	0.0000	0.0000
H_2O	0.0000	0.0067	0.1230	0.0800
LHV (Btu/Ib)	**21501.0**	**1823.0**	**1862.0**	**2495.0**
LHV (Btu/scf)	**959**	**120**	**120**	**120**

PART LIFE ANALYSIS

The durability of hot section has always been of interest to the operators of gas turbines. This has arisen because 40 – 60 percent of the maintenance costs of the unit are attributable to the repair and replacement of these high value parts. However, the increased gas turbines usage, for example in combined cycle power plants, for base load and intermediate duty power generation, has given an impetus to develop improved methods of assessing the condition and useful safe life expectancy of these parts. There is a considerable economic incentive either to extend the total lives of these components, or to increase the interval between inspections and replacements.

Larson and Miller [2] introduced a very useable concept of a time-temperature parameter in the form T(C + log t), based on the rate theory which can be used to estimate the influence of increased metal temperature on the creep life of turbine hot sections. This parameter is known as the Larson Miller Parameter (LMP). A value of 20 was proposed for C while the temperature, T is taken in absolute units and time t is in hours. In general term the following equation is used:

$$\text{Stress} = \text{Function of (LMP)} \tag{5}$$

where

$$LMP = (T + 460)\,(20 + \log_{10} t)*10^{-3}$$

Under design condition, the Siemens SGT6-5000F first stage nozzle and rotor blades are estimated to have a creep life of 48000 hours based on the manufacturer's recommended replacement interval for those parts. The design metal temperature is estimated at 1619°F, and using the above information, the LMP is calculated to be 51310. From this, the time to failure at different metal temperatures can be determined.

RESULTS AND DISCUSSION

The power output of gas turbines fired on full load with natural gas follows ambient air density and falls off considerably at high ambient temperatures. Syngas, diluted with H_2O and N_2 for NOx control, typically has only 15 % of the volumetric heating value compared to natural gas and therefore requires about seven times higher flow rate to maintain the same turbine inlet temperature This allows the turbine to produce more power, up to a theoretical increase of 20% when fired to the same metal temperature as the natural gas, the lower the heating value of the syngas, the higher the power produced due to increased flow through the turbine as shown in Fig. 3. Mechanical capability, surge margin and Mach number restrictions limit this capability, but those limits are not considered in the results presented in Fig. 3. The actual limits are different for each machine output.

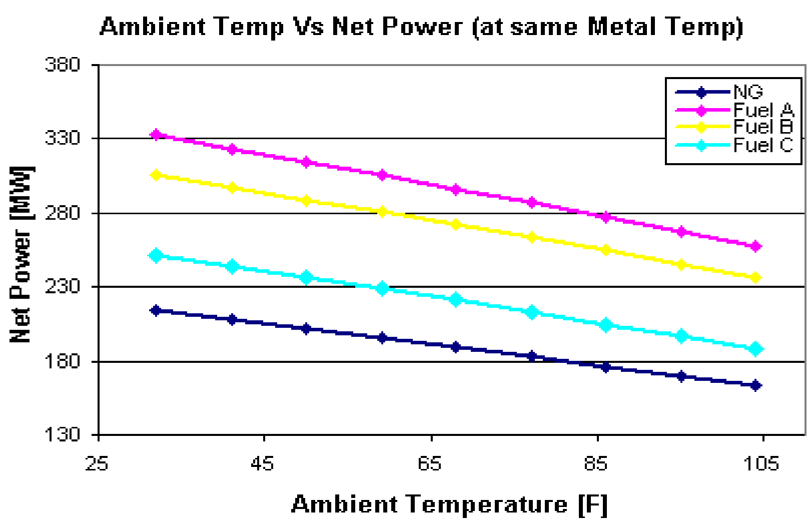


Figure 3. Influence of ambient temperature on power output at same metal temperature

Figure 4 shows the power output of the gas turbine when fired at the same firing temperature as the natural gas. Fuels A, B and C show a respective average increase in power output of about 5, 8 and 23 percent when compared with the same turbine fired with the same metal temperature as the natural gas. However, such increase may not be considered advantageous as it is accompanied with a considerable reduction in the life fraction of the turbine hot sections due to rise in metal temperature across the turbine sections.

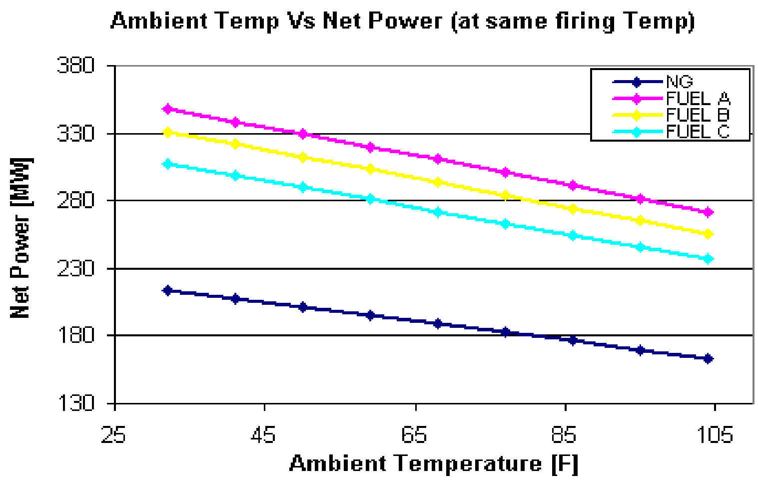


Figure 4. Influence of ambient temperature on power output at the same firing temperature

As the turbine inlet temperature increases, the heat transferred to the turbine hot sections also increases. The level and variation in the temperature within the blade material (which causes thermal stresses) must be limited to achieve reasonable durability goals. Creep life of metal components in the hot section of gas turbine is extremely sensitive to metal temperature.

The creep life of a gas turbine fired at the same firing temperature with a natural gas, syngas fuels A, B and C is shown in Fig. 5. For a syngas with only 12.1 % by volume of H_2 (fuel A), the creep life is reduced by about 20 % when compared with the natural gas at 59ºF ambient temperature. It can be seen that the percentage by volume of hydrogen content in the syngas fuels significantly impact the life of the hot sections as a result of higher flame temperature for hydrogen-rich fuels and also the moisture content of combustion products, the higher the hydrogen content, the higher the water content of the product of combustion and the hotter the metal temperature will become, thereby reducing the relative life fraction of the turbine hot section as shown in Fig. 5.

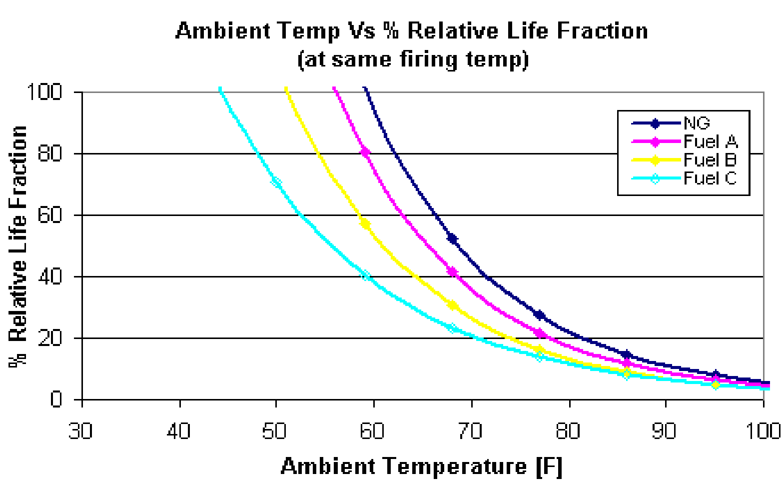


Figure 5. Relative life of turbine hot sections fired with different fuels.

Generally, for a given mixture temperature, the higher the vapor carried by the mixture, the more heat will be transferred to the blades and vanes. The moisture content of airflow through a gas turbine is also amplified by evaporative cooling devices thereby increasing the overall internal heat load of the system. In order to maintain the durability of the hot sections, GE therefore recommends that the firing temperature be reduced as water vapor content increases [3].

It should be noted that the analysis presented in Figure 8 does not represent an exhaustive analysis of all the factors affecting turbine hot section life. Other factors affecting turbine hot section life which have not been taken into consideration include the type of service, number of starts and full load trips and material stress and strain properties. See [4] for further information.

The relationship between the natural gas firing temperature and "derated" temperatures for the various syngases needed to maintain the same first stage nozzle metal temperature as the natural gas case is shown in Fig. 6. It can be seen that both the hydrogen content and the H_2O of the exhaust gas of the syngas combustion play a significant role in the "derated" temperatures. The higher the hydrogen contents (see Table 2), the higher the H_2O in the exhaust (see Fig. 7) and also the more the firing temperature must be "derated" compared to the natural gas firing.

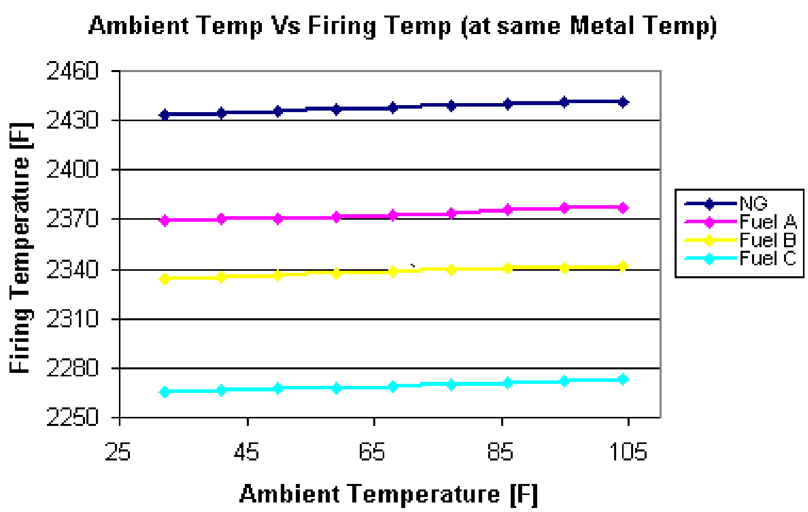
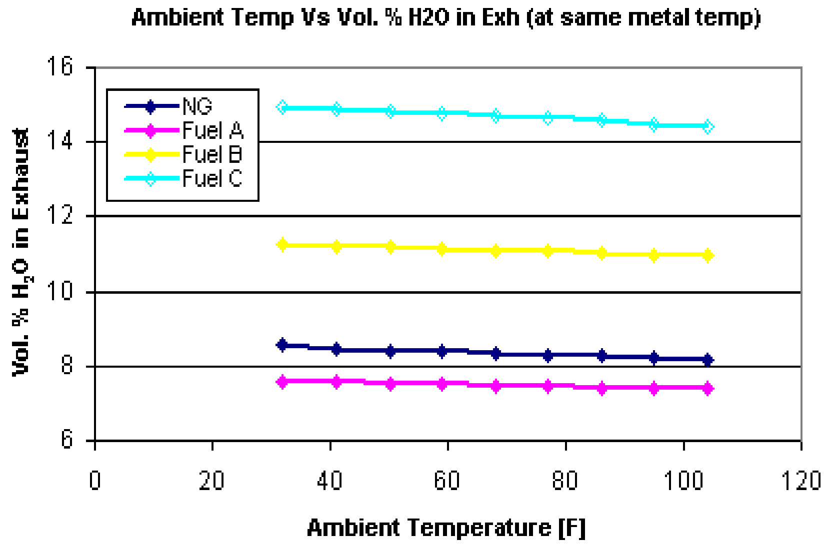


Figure 6. Derated firing temperature necessary to maintain metal temperature

In Fig. 7, variations of the exhaust water content with ambient temperature for the same metal temperature are shown for the natural gas, syngas fuels A, B and C. The higher the hydrogen content, the higher the moisture content which leads to increase in heat transfer in the turbine hot sections. The emission measurements were calculated at the same metal temperature of 1619^{o}F not only for the three different fuel tested, but also for the natural gas.



Figure

It can be seen that as the hydrogen content in the fuel increases from fuel A to C, the water content of the combustion products also increase in the same order. Also, we noticed that the percentage life fraction of the hot section as shown in Fig. 5 decreases in the same order from fuel A to C; showing that the higher the water content of the products of combustion, the shorter the life of the turbine hot section will become. The temperature to which the firing temperature must be reduced in order to maintain the same hot section metal temperatures as experienced with natural gas firing is correlated in terms of the volume percentage of the hydrogen content in the syngas and the lower heating value as $T_f = 13.312(\text{Vol. \% } H_2)^{0.69}$ and $T_f = 5\text{x}10^{-07}(\text{LHV})^{2.52}$ respectively.

CONCLUSION AND RECOMMENDATIONS

The present study documented the fundamental impacts of firing syngas in combustion turbines in order to indicate the appropriate amount of reduction in firing temperature needed to maintain the same hot section metal temperatures as experienced with natural gas firing. The percentage by volume of hydrogen content in the syngas fuels significantly impact the life of the hot sections as a result of higher flame temperature for hydrogen-rich fuels and also the moisture content of combustion products. Correlations were obtained indicating the level of firing temperature reduction, necessary for hot section durability, in terms of the volume percentage of the hydrogen content in the syngas and the lower heating value of the fuel.

Establishing both thermal and environmental degradation behavior and potential lifing of turbine hot sections requires the consideration of wide range of factors, including the detailed analysis of the type of service, number of starts and full load trips, material stress and strain properties, mechanical requirements and life criteria. It is therefore recommended that research in this area be carried out using both numerical computations and experimental data to ascertain the extent to which these factors impact turbine field operations and performance.

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