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Green Engines: Possible Damages by Firing Alternative Fuels and Protection

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Abstract

With the rising cost of fossil fuels along with greenhouse gas emission such as NO_x and CO_x, use of alternative fuels such as syngas and biofuels is intense interesting, and in the meantime using ceramic matrix composites that eliminate the need of film cooling in combustors, vanes and other hot section components to improve the efficiency of gas turbine engine and reduce the NO_x and CO_x emission becomes increasingly attractive for green engines. However, the alternative fuels have an increased hydrogen/carbon ratio; in turn during combustion it produces more water vapor than the conventional jet fuels. The increased water vapor level will have an impact on the protective oxide scale developed on the gas turbine hot section components, particularly on those made of SiC/SiC ceramic matrix composites (CMC), leading to an accelerated degradation of the turbine components. In addition, some alternative fuels derived from biomass may contain alkali elements such as potassium, sodium and calcium, as well as chlorine, sulfur and/or phosphorus, which may result in possible corrosion of the hot section components in gas turbines, leading to premature failure during service. This paper will review some of the alternative fuels and their combustion products, the possible damages to gas turbine hot section components, as well as some potential protective coatings that may mitigate such damage.

Keywords: Gas turbine; Alternative fuel; Ceramic matrix composite; Environmental barrier coating

Introduction

With the rising cost of fossil fuels (oil and natural gas) along with greenhouse gas (GHG) emission such as NO_x and CO_x, use of alternative fuels such as synthesis gas (syngas) and biofuels becomes increasingly attractive [1-3]. Syngas is a gas mixture that contains hydrogen and carbon monoxide generated by the gasification of a carbon containing fuel, such as coal or municipal waste [4]. Biofuels are produced from recently living organisms, most often referring to plants or plant-derived materials [5]. While syngas will increase the water vapor content of the combustion gas, the biofuels and their combustion products mainly contain alkali elements such as potassium, sodium and calcium, as well as chlorine, sulfur and/or phosphorus [6-10]. These may accelerate the degradation process of the hot section components of gas turbine engines such as combustor liners, nozzle guide vanes and turbine blades, leading to premature failure during service [11-13]. This paper will review some of the alternative fuels and their combustion products, the possible damages to the gas turbine hot section components by the combustion products, as well as some potential protective coatings to mitigate such damage.

Properties of Jet Fuels and Some Alternative Fuels

The rising costs of fuel and potential environmental benefits, along with an increasing desire to enhance the security of fuel supply have driven feasibility and viability assessment studies of alternative renewable fuels for commercial aviation applications. Among those studies fuels derived from biomass or synthesis from coal and natural gas via the Fischer-Tropsch (F-T) process [14] are of particular interest, with other alternative biomass based fuels, e.g. fatty acid methyl ester (FAME), also being considered. The properties of some jet fuels and fuel blends are listed in Table 1 [15]. It is noticeable that the hydrogen to carbon (H/C) ratio increases with the increase of biofuels volume.

The overall particulate matter (PM) number emissions over the International Civil Aviation Organization (ICAO) Landing Takeoff (LTO) Cycle are reduced when burning the candidate alternative fuels using a CFM56-7B commercial jet engine [15], and the results are shown in Table 2. It is believed that both fuel aromatic content and H/C ratio will influence PM emissions.

For commercial jet engines, sulfur from the fossil fuel is generally limited to 0.3%; however, as reported in literatures, some biofuels may contain alkali elements such as potassium, sodium and calcium, as well as chlorine, sulfur and/or phosphorus [6-10].

Possible Damages to the Gas Turbine Engine Components by Burning Alternative Fuels

As the alternative fuels have higher H/C ratio, during combustion it will produce increased amount of water vapor than the conventional jet fuel. As a result, the increased water vapor level may have an impact to the hot section components in gas turbine engines, such as combustor liners, nozzle guide vanes and turbine blades.

In modern aircraft engines, hot section components are often protected by oxidation/hot corrosion resistant metallic coatings or thermal barrier coating (TBC) systems, composed of an yttria-stabilized-zirconia (YSZ) ceramic topcoat and a metallic bond coat deposited on the superalloy substrate [16]. The YSZ topcoat provides heat insulation to the components, while the metallic bond coat

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provides adhesion between the YSZ topcoat and superalloy substrate as well as oxidation and hot corrosion protections. The blades of high pressure turbines (HPTs) that withstand most severe thermal cycling condition are usually protected by the state-of-the-art electron beam physical vapor deposition (EB-PVD) produced TBC system, which has a chemical vapor deposition (CVD) produced Pt-modified NiAl bond coat Figure 1.

β type Pt-modified NiAl coatings, produced by platinum electroplating followed by CVD aluminizing, has excellent oxidation resistance and Type I hot corrosion resistance, and has a higher temperature capability than the conventional MCrAlY type oxidation and hot corrosion resistant coatings. However, a recent study shows that it degrades faster in water vapor environment by depleting Al from the β-NiAl phase at high temperatures Figure 2 [17], leading to a reduction of lifetime. Such degradation proceeds via the reaction between water vapor and the oxide scale developed on the surface of Pt-NiAl coating, $Al_2O_3+3H_2O= 2 Al(OH)_3(g)$. Influence of water vapor on another type of oxidation/hot corrosion resistant coating, i.e. the MCrAlY type coatings, is barely reported.

In gas turbine engines, metallic components that experience high temperature exposure are protected by TBCs, along with internal cooling through the cooling channels, which will also generate NOx emission. The use of ceramic or ceramic matrix composite (CMC) components becomes increasingly attractive because of the elimination of the need for film cooling, with the candidate ceramic materials being SiC, Si_3N_4, SiC/SiC CMC, and oxide/oxide CMCs. However, silicon based ceramic materials will be oxidized to form a SiO_2 scale on the component surface upon thermal exposure, which will react with water vapor at high temperatures, leading to volatilization of SiO_2 Figure 3 [18], also, SiC may react with water vapor directly. The reactions can be described as

$$SiC+3H_2O(g)=SiO_2+CO(g)+3H_2(g) \tag{1}$$

$$SiC+3/2O_2(g)= SiO_2+CO(g) \tag{2a}$$

$$SiO_2+2H_2O=Si(OH)_4(g) \tag{2b}$$
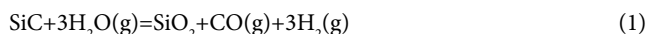
During combustion of biofuels that derived from biomass and municipal waste, it may produce some products containing alkali elements such as potassium, sodium and calcium, as well as chlorine, sulfur and/or phosphorus [6-10]. Although alkali chlorides are highly detrimental to the metallic components by reacting with the protective oxide scale at around 600°C [19], because gas turbines operates at very high temperatures, impact of alkali chlorides to gas turbine hot section components may not be as significant as sulfates in Type I hot corrosion [12]:

$$2NaCl(g)+SO_3(g)+ H_2O(g)=Na_2SO_4(l)+2 HCl(g) \tag{3a}$$

$$Al_2O_3+Na_2O(\text{ in }Na_2SO_4)=2 NaAl O_2 \tag{3b}$$
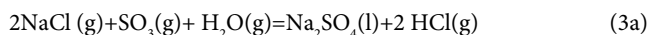
For the CMC based components, molten sodium sulfate also partially decomposes and dissolves the protective silica scale [20-23].

Potential Protective Coatings to Prevent Damage from Water Vapor

Thus, the major problem in gas turbine engines burning alternative fuels is apparently water vapor formed during combustion, as a result of the high H/C ratio of the fuel. Water vapor consequently reacts with the protective oxide scales that developed on the component surfaces, making the oxide scales less protective and therefore leading to a faster degradation of the protective coating or substrate material, compared

to in the dry oxidation environment. Environmental barrier coatings (EBCs) to protect gas turbine components from water vapor attack at high temperatures are under developing, among which Ta_2O_5-based EBCs appear to be effective in inhibiting water vapor induced volatilization of SiO_2 scale Figure 4 [24]; however, Ta_2O_5-based coatings are not sufficient to act as a stand-alone EBC.

	Fuels and fuel blends					
	Jet-A	Jet-A1	20% FAME / 80% Jet-A1	40% FAME / 60% Jet-A1	50% F-T / 50% Jet-A1	100% F-T
Fuel identifier	Jet A	Jet A1	20% FAME	40% FAME	50% F-T	100% F-T
Specific gravity @ 15°C	0.803	0.797	0.808	0.825	0.776	0.755
Kinematic viscosity @ -20°C (mm²/s)	5.78	4.27	4.74	5.62	4.4	4.65
EI CO_2 (g/kg fuel burned)	3155	3155	3045	2942	3127	3100
Heat of combustion (kJ/kg)	43302	43300	42000	40300	43600	44100
H/C ratio	1.92	1.92	1.94	1.94	2.04	2.17
Aromatic content (vol.%)	12.3	18.5	14.8	11.1	9.25	< 0.2
Oxygen content (wt.%)	0	0	3.4	6.6	0	0

Table 1: Properties of fuels and fuel blends.

	Alternative fuel			
	20% FAME	40% FAME	50% F-T	100% F-T
PM number reduction	22% ± 7%	35% ± 6%	34% ± 7%	52% ± 4%
PM mass reduction	20% ± 8%	52% ± 5%	39% ± 7%	62% ± 7%

Table 2: Overall PM number and mass reductions over the LTO cycle achieved using candidate alternative fuels
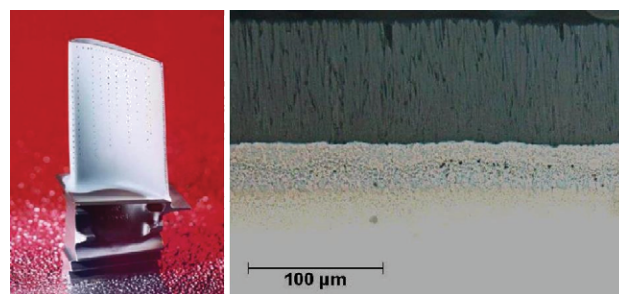

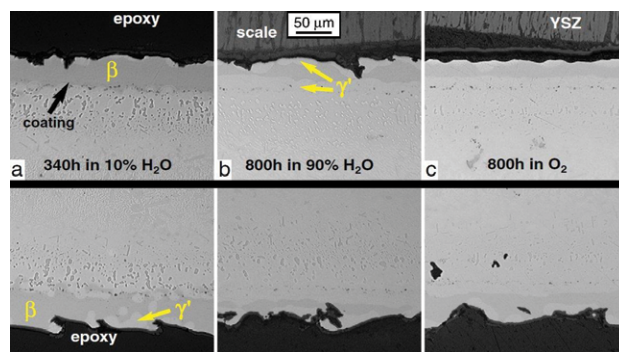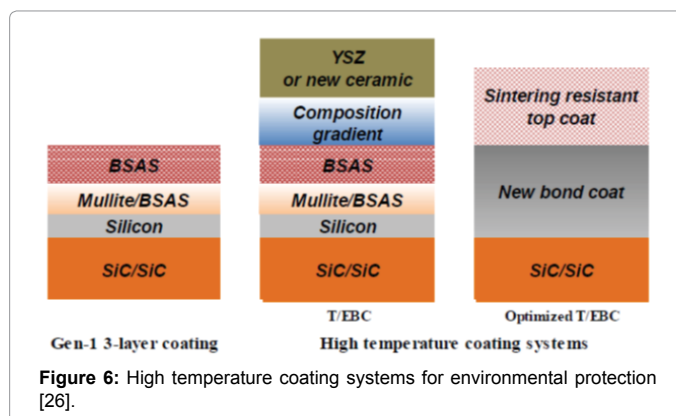**Figure 1**: HPT Stage 1 blade protected by Pt-NiAl + EB-PVD YSZ [16].

Figure 2: Depletion of Al from β type Pt-NiAl in water vapor environment at 1150°C [17].

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The EBCs to protect SiC/SiC CMC from water vapor attack have to be very dense, because any open pores and/or cracks in the EBCs are openings for water vapor to penetrate to the SiC/SiC matrix material. A multilayered Si/mullite+BSAS (barium-strontium-aluminum-silicate)/ScSiO$_5$ EBC for SiC/SiC CMC vane is shown in Figure 5 [25]. The Si layer is applied to get a strong bond to the SiC/SiC matrix material, whereas the mullite+BSAS layer is applied to improve the crack resistance of the EBC layer. As the cross section shows, the EBC layer is nonporous, which prevents water vapor penetration.

Moreover, the design surface temperature for the CMC components is expected to exceed the BSAS thermal stability limit, thus, in addition to increase the EBC thickness, materials having high temperature capability and low thermal conductivity are required. In the meantime, environmental protection of the CMC substrate from the recession and hot corrosion will still be needed. One of the approaches to "building" a high-temperature T/EBC system would consist of an added high-temperature ceramic layer, for example, zirconia-based, on top of the three-layer BSAS type EBC system Figure 6 [26]. A transition layer with an intermediate coefficient of thermal expansion (CTE) will be needed to accommodate the CTE mismatch between the BSAS layer (about 5 ppm/°C) and the top ceramic layer (about 10 ppm/°C in the case of stabilized zirconia). This approach will result in a five-layer

Figure 3: Sintered α-SiC, 100 hours at 10 atm and 1200°C, shows volatilization of SiO$_2$ in water vapor [18].

Figure 4: Bare and APS-Ta$_2$O$_5$ coated AS800 (silicon nitride), 500 hours at 2 atm PH$_2$O and 1315°C [24].

Figure 5: Environmental barrier coating on SiC/SiC CMC, 300 1-h cycles at 1400°C in water vapor [25].

Figure 6: High temperature coating systems for environmental protection [26].

coating system which presents challenges in terms of processing, meeting thickness requirements, and cost. Therefore, new types of materials that could replace the three-layer EBC system, provide the environmental protection, and serve as a bond coat for the top ceramic layer are currently under development.

Concluding Remarks

Use of alternative fuels such as syngas/biofuels and ceramic matrix composites can help to reduce greenhouse gas emission such as NO_x and CO_x; however, water vapor and possible molten salts formed during alternative fuel combustion may damage gas turbine hot section components by reacting with the protective oxide scales that developed on the component surfaces. Water vapour results in volatilization of the protective SiO_2 scale on the CMC surface leading to faster degradation of the CMC; however, influences of water vapor on oxidation and hot corrosion resistant metallic coatings, such as Pt modified NiAl and MCrAlY coatings, are not well explored, which deserve further and detailed investigation.

In gas turbine engines, environmental barrier coatings protect engine components from the volatilization and the resulting recession caused by water vapour and molten salt, but coating structure and deposition process need to be optimized. Moreover, thermal/environmental barrier coating systems merit continuous development to meet the requirement of high design temperature for the gas turbine hot section components. Furthermore, simplicity and affordability of the T/EBC systems warrant consideration.

Acknowledgement

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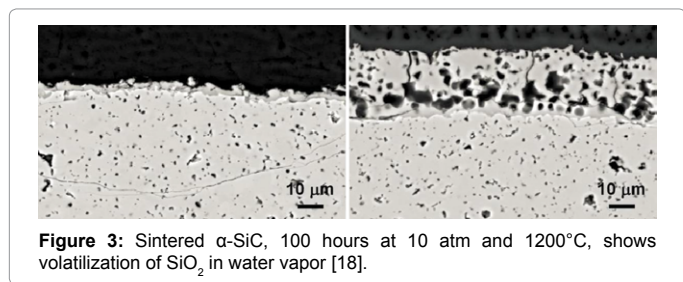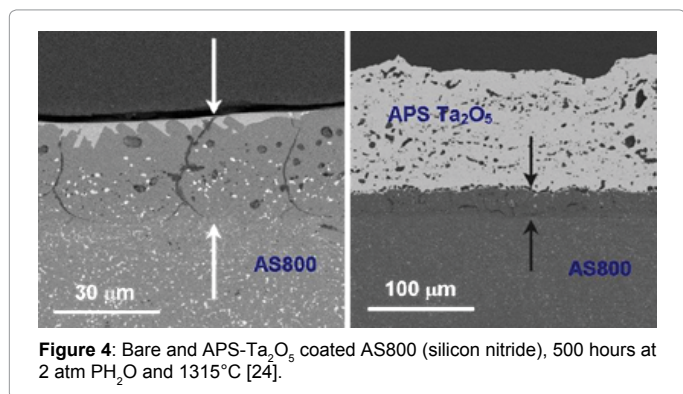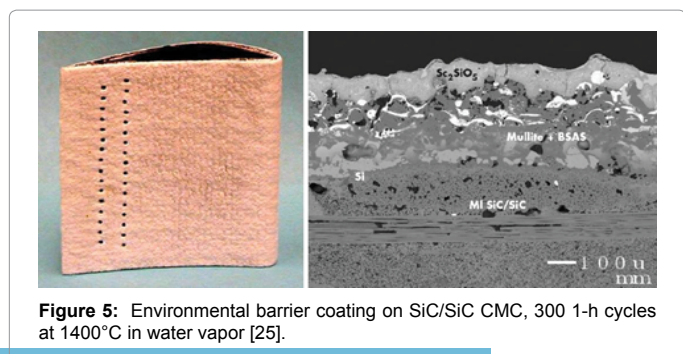
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