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Research article

Formation of deposits from heavy fuel oil ash in an accelerated deposition facility at temperatures up to 1219 °C

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ABSTRACT

Some industrial gas turbines are currently being fired using heavy fuel oil, which contains a small percentage of inorganic material that can lead to fouling and corrosion of turbine components. Deposits of heavy fuel oil ash were created in the Turbine Accelerated Deposition Facility (TADF) at Brigham Young University under gas turbine-related conditions. Ash was produced by burning heavy fuel oil in a downward-fired combustor and collecting the ash from the exhaust stream. This ash was then introduced into the TADF and entrained in a hot gas flow that varied from 1101 °C to 1219 °C. Sulfur dioxide was introduced to the system to achieve 1.1 mol% SO_2 in the exhaust to simulate SO_2 levels in turbines burning heavy fuel oil. The gas and particles were accelerated to over 200 m/s before impinging on a nickel-based superalloy coupon and forming deposits. The ash deposits were collected and the capture efficiency, surface roughness, and deposit composition were measured. The deposits were then washed with deionized water, dried, and the analysis was repeated. As the gas temperature increased, there was no effect on capture efficiency and the post-wash roughness of the samples decreased. Washing aided in the removal of sulfur, magnesium, potassium, and calcium.

1. Introduction

Particle deposition on turbine blades is a concern when combusting fuels with inorganic matter that can form ash particles that then impinge on and stick to hot turbine components. Areas of concern have included the use of coal-derived fuels such as coal-water slurries and syngas, with the latter being of more recent interest. As combustion temperatures increase, particle deposition is more likely to occur. Particle deposition in gas turbines can adversely affect turbine performance in a variety of ways: clogging film cooling holes, thus reducing film cooling effectiveness [1]; changing flow patterns around turbine airfoils and decreasing efficiency [2]; and depositing corrosive elements such as Na and V [3]. Even at low ash content, particle deposition is a concern. Cleaned syngas can have an ash concentration close to 0.1 ppmw. Another fuel used in land-based gas turbines is heavy fuel oil (HFO). HFO is a heavy residue collected from the refining of crude oil. HFO, however, can have ash contents that are several orders of magnitude higher than cleaned syngas [4]. For example, Tovar et al. performed combustion experiments using HFO with 0.21 wt% ash [5].

HFO often contains significant levels of corrosive elements such as sodium, sulfur, and vanadium. In an effort to change ash and deposit characteristics and reduce corrosion, magnesium-based additives can be added to HFO [6–9]. A primary goal is to prevent deposition of vanadium pentoxide (V_2O_5) by instead forming magnesium orthovanadate ($Mg_3V_2O_8$). When sulfur is present in the HFO, sulfur dioxide and sulfur trioxide (SO_2/SO_3) are produced during combustion. The SO_3 can react with magnesium oxide (MgO) to produce magnesium sulfate ($MgSO_4$). This can inhibit the formation of magnesium orthovanadate by depleting the amount of available magnesium in the system. However, $MgSO_4$ is water-soluble and is more desirable than MgO deposits, which can also form and which are non-soluble in water and harder to remove.

The purpose of this study is to investigate the deposition behavior and characteristics of flyash produced from the combustion of HFO in gas turbines. HFO flyash was produced in the experiments performed by Tovar et al. [5] and provided to the authors for the current study. The flyash was then used to produce ash deposits that were analyzed to determine trends in capture efficiency, deposit roughness, deposit chemistry, and deposit solubility.

2. Experimental setup

The experiments for this study were performed in the Turbine Accelerated Deposition Facility (TADF) at Brigham Young University. The following sections will describe the design of the TADF, the materials (ash and metal coupons) used for this study, the conditions at

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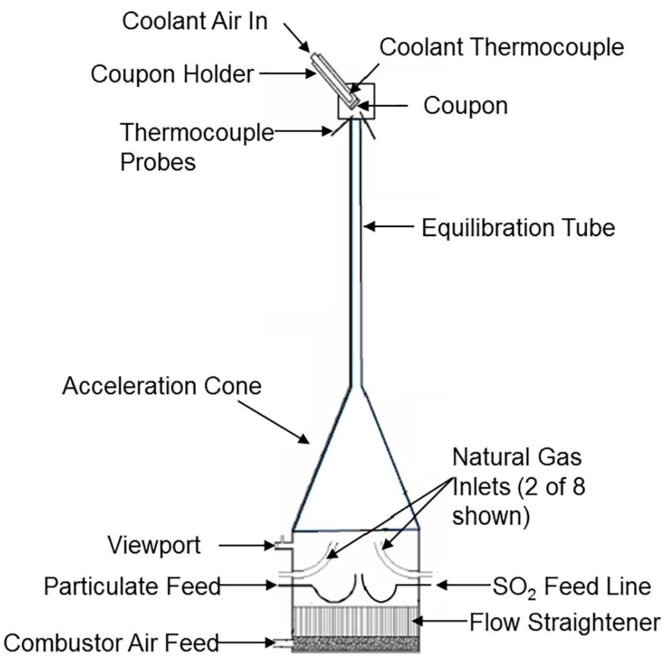

Fig. 1. Schematic of the TADF at BYU.

which the tests were performed, and how the data were analyzed. Additional details concerning the TADF and analysis techniques can also be found in [10].

2.1. Deposition facility

The TADF is shown in Fig. 1. The TADF was designed to simulate deposition that occurs in land-based gas turbines with particle-laden flow on a laboratory scale. The deposition occurs in an accelerated manner, originally simulating 10,000 h of exposure time with 0.112 ppmw of particulate in 4 h by increasing particle loading to 280 ppmw in the exhaust gas. The use of accelerated deposition testing was validated by Jensen et al. [11].

The combustion chamber is located at the base of the TADF. Natural gas is burned in the combustor and the facility is capable of reaching gas temperatures (T_g) similar to the turbine inlet temperature (TIT) of modern gas turbines. Ash is fed into the base of the combustor and flows upward with the combustion gases through a cone that converges toward a 0.8 m long equilibration tube with an inner diameter of 27 mm. The cone accelerates the gas to velocities of 200 m/s and greater. The acceleration cone and equilibration tube is a 2-piece configuration with a SiC cone and a quartz tube. The quartz equilibration tube is easily removed, weighed, and replaced when necessary.

The particulate laden gas exits out the top of the equilibration tube and impinges on a nickel superalloy coupon held at a 45° angle directly above the equilibration tube. This coupon is the surface upon which deposition occurs. The rate at which deposition occurs is dependent upon the impingement angle of the gas stream on the coupon, with deposit thickness (measured normal to the surface) increasing as impingement angle increases [11]. The 45° angle was chosen to allow for an appreciable amount of deposit to be collected in the 1 h time frame, and is somewhat representative of the leading edge portion of turbine vanes and blades.

The coupon holder has an open chamber behind the coupon that allows coolant air and water to flow behind the coupon for backside cooling, or film-cooling if the coupon has been equipped with film-cooling holes. For this study, no coolant was used and the area behind the coupon was packed with insulation.

2.1.1. Sulfur dioxide feed line

In order to more closely simulate the combustion environment for the HFO ash experiments, an additional feed line was added to the base of the TADF. This feed line allowed for the introduction of SO_2 into the combustion chamber. The necessity to maintain the levels of SO_2 in the system are discussed under the test conditions section of this paper.

2.1.2. Coupons

Metal coupons were provided by industrial contacts. The coupons were made of a nickel based superalloy specific to the turbine manufacturer. An example of the coupons used in this study can be seen in Fig. 2. Each coupon had a front side diameter of 2.5 cm and was 0.3 cm thick. To protect the coupon holder from the high gas temperatures, a silica faceplate was affixed to the front of the holder. The front of the faceplate was designed to be flush with the front face of the coupon to avoid creating edges or protrusions that would alter the flow and deposition patterns along the coupon.

Bare metal coupons were used in this test series. The deposit was removed from the coupons after the deposit analysis was complete and the coupons were cleaned, polished and reused in subsequent tests.

2.1.3. Heavy fuel oil ash

The HFO ash was a blend of ash samples provided by Tovar et al. [5]. Raw HFO was first washed to reduce sodium and potassium levels to typically 2 ppm or less and then filtered. The HFO was then burned in a downward-fired combustor. Prior to entering the burner nozzle of the combustor, a magnesium additive was injected into the HFO. During the combustion process, portions of the flue gas were directed through two bag filters and a cyclone separator in order to collect the ash for

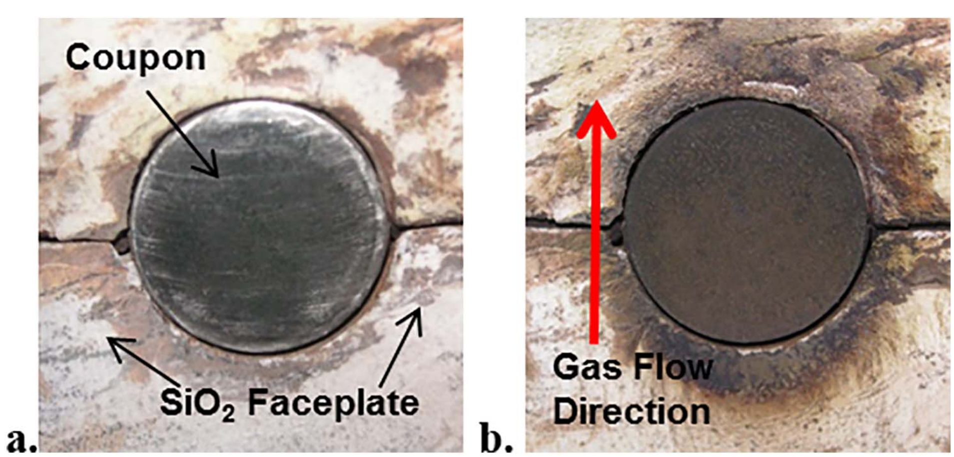

Fig. 2. a) Coupon and faceplate before any deposition occurred. b) Coupon and faceplate after deposition. Only ash deposited on the coupon was used in calculating capture efficiencies.