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An innovative high temperature solid particulate erosion testing system

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ABSTRACT

A new high temperature solid particulate erosion test system has been designed and built to improve the quality of high temperature erosion tests. The new test system is designed to carry out experiments at temperatures up to 900 °C and particle velocities up to 300 ms^{-1}. A key feature is the use of commercial "air torch" technology to provide the necessary high air flow rates at elevated temperature giving the whole system a relatively small footprint. Measurements of erosion rate are revolutionised by two different forms of in-line measurement of wear to the sample. This new technology largely replaces the need for interrupting the test, cooling the test samples, and weighing at periodic intervals which can mean that a test with a total exposure of 30 min to erosion by particles at high temperature can take most of a week. The two new technologies employed use a high precision balance to measure the *in situ* weight of the samples whilst they are still at test temperature, and the use of a custom designed blue laser triangulation system to measure the shape of the wear scars *in situ* and at temperature.

The use of the new test system is illustrated by preliminary results of experiments from coated and uncoated Nimonic 80 A.

1. Introduction

In 2010, the eruption of the Icelandic volcano Eyjafjallajökull, ejected a plume of fine glass-rich ash into the atmosphere to a height of over 8 km (5 miles). Located directly under the jet stream this eruption went on to cause severe disruption as the ash was carried over northern Europe and into its busy airspace. The impact to air travel was phenomenal, with airspace intermittently closed for 6 days over different parts of Europe, affecting more than ten million people and costing an estimated £1.1 billion. The major concern for aviation was the ingestion of the volcanic dust into the engines, which would then become molten and, on passing through the engine solidify on cooler sections leading to engine failure. There was also the additional concern that the erosive nature of the ash would 'sandblast' windows and navigation lights reducing visibility for the pilots and damage the leading edges of blades and wings as happened in 1992 to a British Airways flight to Auckland. Consequently, the Civil Aviation Authority set new guidelines [1] allowing flights when the ash loading was between 200 and 2000 μg per cubic metre of air, a figure which was subsequently revised up to 4 mg per cubic metre of air [2]. This is an extreme example of the impact of High Temperature Solid Particle Erosion (HTSPE) which occurs routinely and impacts the efficiency of, for example, turbomachinery and wind turbines. Reliable and repeatable test methods are required to be able to generate and validate such safety critical guidelines, alongside reliable, controllable and instrumented apparatus.

Up until 2014 there were no recognised standard test methods for HTSPE testing. Testing of materials up to that point was generally based around the ASTM G76 test method, which has some short comings with regards to HTSPE (*e.g.* room temperature, limited velocities, and geometries) but was nonetheless used and is generally considered to be suitable for ranking material performance. Since then, ASTM International have published a standard test method for High Temperature Solid Particulate Erosion [3] which addresses many of the measurement issues, and provides recommendations for apparatus design. Whilst this standard provides the framework and guideline for the test it does not advance the robustness of the test through improved metrology.

In 2013 the Electric Power Research Institute (EPRI) reported on a round robin exercise they conducted [4] to aid the development of the ASTM standard [3]. The round robin included participants from numerous countries with a variety of apparatus designs. When comparing the apparatus it is evident that there are a number of designs and approaches different laboratories have taken covering a range of experimental parameters, for instance, how the gas is heated, how the velocity is measured, acceleration lengths used, nozzle designs, *etc.* These differences in testing

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approaches can make the comparison of erosion results between laboratories difficult. The ASTM standard should address this by having a standardised approach. However, there still remain significant variations in equipment used and the level of instrumentation and control employed. Unlike in areas such as mechanical testing, where the apparatus used broadly follow a similar design from manufacturer to manufacturer, in tribology there is not one accepted design for HTSPE test apparatus, with many test facilities being constructed to meet particular needs, such as wear in pipes [5], in boilers by fly ash [6] and in flow channels by sand [7] to name but a few. The measurement of test parameters and material degradation *in situ*, whilst viewed as important, is rarely conducted during a HTSPE test. Test parameters such as the gas/particle velocity, erodent dimensions and temperature are commonly measured and defined in calibration tests prior to the erosion experiment, but hardly ever considered during the actual test. At room temperature, apparatus developed and reported in the literature have been able to include measurement methods for parameters such as particle velocity, by including timing gates [8,9]. However, as temperatures increase adding in-line instrumentation becomes progressively more difficult.

Outside of the EPRI programme and intercomparison exercise described by Swaminathan et al. [4,10], there has been a growing realisation within the testing community that there are also major limitations in terms of the understanding and control of uncertainties associated with the measurements undertaken during the test, and their applicability to real industrial applications. Current practices have the potential to result in large errors in measurement, for instance the normal method for velocity measurement of the erodent particles is through a twin disc test system, where rotating discs are used to give a measure of the velocity. This method has been shown to have the potential for measurement errors of the order of 20–30% [11]. As part of the EURAMET funded METROSION project a new test facility has been designed and constructed with the aim of producing a versatile apparatus with embedded instrumentation to monitor and control the temperature of the gas, sample and particles, to measure and control the gas velocity and to measure the mass change and erosion scar volume *in situ* during the test. Enabling the *in situ* measurement and control of the gas and particle velocity, the temperature of the system and the geometry of the erodent, will provide a test with greater precision and control, to replicate the required industrial conditions. The inclusion of *in situ* evaluation of the mass change and volume change of the sample provides a real time measurement of the erosion process, but also avoids thermally cycling the sample for the *ex situ* mass and surface measurements at room temperature. This enables the erosion test to be conducted without interruption, thereby allowing the test to be completed in a matter of hours as opposed to a number of days. The following paper will provide a general description of the METROSION apparatus and present preliminary results on coated and uncoated materials illustrating the performance of the *in situ* measurement methods.

2. Apparatus and in *situ* measurement systems

The design of the METROSION HTSPE apparatus is shown in Fig. 1 which highlights the major innovative components of the design, namely the compact air heater (also shown in Fig. 2), mixing and delivery nozzle, and the *in situ* measurement systems locations within the apparatus.

The carrier gas for the erosive particles is provided by an air pump operating at a maximum pressure of 1 bar, but providing a gas flow rate of 400 $m^3 h^{-1}$ (235 cuft min^{-1}). This is then heated

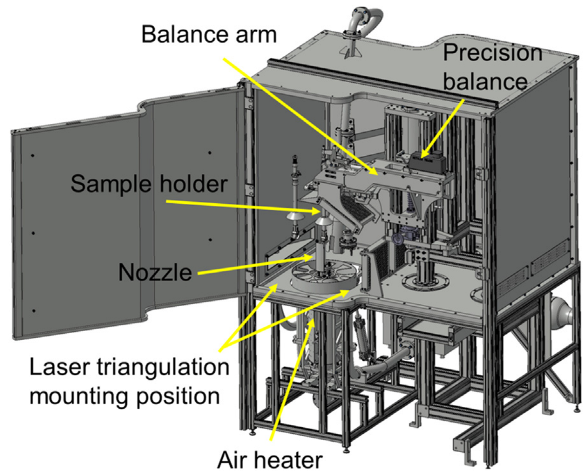

Fig. 1. CAD design of the METROSION HTSPE apparatus showing the location of the major components.

Fig. 2. Air heater used to heat the erodent carrier gas.

by a commercial air heater unit, approximately 20 cm in length and 9 cm in diameter housing a 17 kW heater bank (shown in Fig. 2). This compact heater is capable of heating the gas to a maximum temperature of 900 °C and allows the NPL rig to avoid the use of high pressure systems, such as those employed at Cranfield University [12], thereby simplifying the operation and avoiding the potential issues associated with high pressure systems and pressure regulations. Once heated the hot gas passes into the nozzle and the erodent particles are introduced into the gas stream either cold or from a heated hopper. The particles are accelerated down the ceramic lined nozzle and exit to impinge on the sample suspended above the nozzle at the required angle. The nozzle and the sample holder are both contained in a furnace to control and maintain the temperature.

During the design process for the nozzle, extensive modelling was used to determine the appropriate dimensions to achieve the desired gas velocities of 300 ms^{-1} at 900 °C. The modelling, and subsequent experimental trials have demonstrated that the combination of air pump, heater and nozzle can achieve these velocities and temperatures. Further details regarding the nozzle