Publishable JRP Summary Report for JRP-i15 (METROSION) Metrology to Enable High Temperature Erosion Testing

Background

In 2010, the eruption of the Iceland volcano grounded all passenger and goods transportation by planes for weeks. The severity of volcanic ash particles eroding the material of the fan blades was not known at the time. Although this was an extreme event volcanic eruptions have continued to threaten the aerospace sector. Similar erosion issues are perennial problems for gas turbines, be they for helicopters, civil aero-engines or for power generation, operating in dusty, sandy or coastal locations. There are currently few facilities available worldwide for the measurement of high temperature solid particle erosion (HTSPE). Those that exist are limited in terms of the particle velocity and temperature. There are also major limitations in terms of the uncertainties associated with the measurements undertaken during the test and their applicability to real industrial applications. Current practice leads to large errors in measurement that needs major improvement, for instance measurements of particle velocity made using the common twin disc method have measurement errors in the order of 20-30%. Errors associated with other critical parameters such as particle temperature, size and size distribution further increase the associated uncertainties in the measurement and characterisation of high temperature solid particle erosion, impacting on the ability to model the phenomena in anything but an empirical manner.

The aim of this JRP is to develop the metrological framework necessary to fully instrument and monitor high temperature solid particle erosion testing. This framework and metrological toolbox will be used and implemented on a test system designed to perform HTSPE tests at temperatures up to 900 °C and with particle velocities up to 300 ms^{-1}. Being fully instrumented, in terms of temperature measurement and velocity measurement, also with fully characterised particles (size, shape and distribution) will enable improved control and precision for HTSPE tests, leading to improved understanding of material performance, mechanisms of HTSPE and the transition points between different mechanisms with respect to the different variable parameters (impact angle, temperature, velocity, etc.).

Ultimately the metrological framework to be developed in this JRP will aid the delivery of critical input parameters and physical understanding and so facilitate the development of improved mechanistic and phenomenological based models to predict materials behaviour and performance under HTSPE conditions.

Need for the project

Erosion and wear can dramatically reduce the efficiency and life of high value components across a range of industrial sectors, for example this form of degradation alone costs the power industry an estimated 200M€ a year in lost efficiency, forced outages and repair costs [1]. Major improvements in the efficiency of power generating plant (7% to 10%) and aero-engines will be made possible by the development of new materials that have improved resistance to high temperature particulate erosion, thereby reducing carbon emissions. To achieve this, improved models and understanding are required necessitating improved and more controlled instrumented tests.

For many years HTSPE testing has been limited to purely being able to rank materials comparatively under conditions which were believed to nominally replicate service conditions. Assessment of the erosion resistance of candidate materials and the development of surface engineering solutions have been hampered by a lack of traceable metrology, such as the measurement of damage, measurement of the temperature of the erosive particles and also the supporting gas stream, plus measurement of the gas stream flow rates, erosive particle size and shape. The lack of control of these parameters has been

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identified as the major contributory cause of a lack of reproducibility in the measurement of erosion damage (up to 100%) by an EPRI (Electric Power Research Institute) workshop [5]).

Without this necessary metrological framework, the development of new materials will still be based on a largely empirical approach. This will significantly delay the improvements that are needed to meet the challenges of reducing environmental impact, improving plant performance and efficiency, so helping to meet the EU targets for CO_2 emissions, the target date for which grows ever closer.

Scientific and technical objectives

To achieve the goals of this JRP the following technical and scientific objectives must be met.

- Measurement of the volume of erosion through *in situ* sensors, capable of measuring depth of damage to a resolution of 1 μm enabling on-line measurement of the erosion rate.
- *In situ* measurement of the velocity of high temperature erodent particles and its distribution. The volume of damage in erosion is highly dependent on the velocity of the erodent particles, so improved accuracy in the measurement of this parameter will significantly reduce the uncertainty in the evaluation of erosion and its modelling.
- High speed measurement of the temperature of high velocity erosive particles and the supporting gas stream at temperatures up to 1000 °C. The performance of materials is critically dependent on temperature because of changes in temperature dependent properties such as modulus, hardness and the transition between ductile and brittle behaviour. Accurate temperature measurement is therefore critical both in the control of the test and in the understanding and interpretation of the results from the test.
- Measurement of the gas stream flow rate and its distribution.
- Measurement and characterisation of the erosive particle size and shape, and consequentially their effect on respective particle speeds. These parameters dictate the detailed damage that takes place when impacts between particles and the target materials occur.
- Determination of the influence of test parameters such as the angle of incidence and the geometry of the test system on the results that are obtained and the repeatability and reproducibility of these results.
- Modelling of the high temperature erosion process to achieve a life prediction capability. The models developed will be compared and validated with the results of experiments carried out within the project to assess the validity of the models.

Expected results and potential impact

This project will provide a step change in the ability of industrial laboratories and research institutes to measure high temperature solid particle erosion (HTSPE). It will enable this through:

- The development of improved metrological test systems for HTSPE,
- Better measurement of damage mechanisms and erosion,
- The development of in-situ and on-line measurement of mass and erosion rates,
- Better control and measurement of test parameters such as temperature and erodent velocity,
- The development of predictive modelling for the performance of materials subject to HTSPE.

The outputs of this JRP will lead to major improvements in the competitiveness of European industry, particularly in industries which rely on or develop engineered surfaces to combat harsh environments or the use of critical materials in high value added applications, such as aerospace, energy, mining and oil and gas. This will be achieved through improved measurement procedures and better understanding of uncertainties in test methods which will increase the confidence and applicability of the results and will enable the development of accurate models based on an improved understanding of erosion and wear. As a result, these methods will lead to a better assessment of in-service component performance and enabling improved design with novel, more durable materials. Additionally, this JRP will enable European manufacturers to provide energy generation solutions, land and aero, with reduced impact on the environment. For example reducing the erosion of the leading edge of turbine blades would result in improved efficiency and thus avoid, in the case of a large power plant (~800 MW), the emission of an extra 250,000 tonnes of CO_2 over the lifetime of the plant. Improved efficiency of high temperature plant will be achieved by enabling higher operating temperatures to be used in power generation plant through improved materials that can withstand HTSPE at higher temperatures than before and through the use of environmentally friendly fuels such as biofuels which would allow operation of power plant with little or no overall impact on carbon dioxide generation.

Current Progress

At the half way point in the JRP, the substrates (Nimonic 80A and X22 steel), coatings (Stellite 6, TiAlN, CrC HVOF coating and a novel multi-layered coating) and erodent's (alumina, silica, chromia and fly ash) have been selected through stakeholder consultation and supplied to the JRP partners. Characterisation of the uncoated substrates and the erodent powders has been completed and a report summarising the measurements and the results circulated to the partners to aid the practical and modelling work.

One of the major tasks in the JRP was the development and upgrading of apparatus to perform the HTSPE tests. Within the project there are currently three rigs which can be used, all three of which have been modified and upgraded to help meet the requirements of the JRP. Additional sensors have been built into the existing high temperature rigs and access ports introduced to allow imaging of the gas stream during a test. The design of the new rig to be housed at NPL has been completed, with solutions to *in situ* mass and erosion scar volume measurement being developed and honed so that they can be incorporated into the apparatus. Finite element continuum physics modelling has been used to develop a design for the nozzle of the HTSPE rig. This modelling has been used to optimise the geometry of the nozzle such that the target gas velocity of 300 ms^{-1} over a temperature range of 25 to 900 °C can be achieved. This model has been validated and used to aid in the modification of the nozzles of existing rigs to achieve higher gas velocities and improved flow.

High speed optical sensors have been developed using novel custom built optics. These high speed optics have been used to image high speed particles and track there movement as they exit the gas nozzle. Integration of these sensors to existing test rigs are current proceeding. These sensors will ultimately be used to monitor the speed of the erodent powders which have been measured using advanced 3D (X-ray Computed Tomography) and 2D (Optical imaging) methods to measure the size and shape of the powders. These measurements are being used to provide a parameter to index the relative erosivitiy of particles using methods and algorithms developed within METROSION. A model of particle erosion (ERROW-SIM) has been developed using a penetration model for incompressible targets which is based on the spherical cavity-expansion approximation[1]. This generic approach has been compared to observations and erosion damage from erosion tests and shows the correct damage accumulation rate and erosion damage that is seen in practical tests. Development of this model progresses with the implementation of a 'particle sticking' feature, which is now being included in the model. In addition a Finite Element model has been created to model particulate erosion. Further work to develop and validate these models and additional models continues.

The ultimate aim of this JRP is to understand the measurement uncertainties and control them to enable more reproducible and representative HTSPE tests. To achieve this it is important to understand the current uncertainties in the test method to be able to gauge the improvement achieved through better measurement, instrumentation and test control. A series of intercomparisons have been completed to determine the uncertainty in routine velocity measurements based on the double disc method. Uncertainties of 30% were found in this study. An intercomparison on the uncertainty in the evaluation of mass change and volume of erosion scars has also been conducted. Preliminary results indicate that the measurement of mass and mass change is very repeatable and reproducible, but the measurement of the erosion scar volume can vary greatly depending on the methods used to measure it. This work continues so that the potential for

[1] M.J. Forrestal, D.Y. Tzou, E. Askari and D.B. Longcope, Penetration into ductile metal targets with rigid spherical-nose rods, Int. J. Impact Engng, Vol. 16, No. 5/6 (1995) 699 - 710

improvements that can be achieved using more advanced measurement methods can be evaluated, and also to understand why there is such variation in some of the volume measurements.

In summary all tasks within the JRP are now active, with the main activities being:

- Substrate materials, coatings and erodents selected and obtained,
- Characterisation of the materials completed,
- HTSPE equipment modified and new apparatus design completed and system build initiated,
- Methods to visualise and measure the shape and size of erodent particles progresses well with methods of computed tomography providing good results with good statistics (several thousands of particles),
- Sensors for *in situ* measurement of the gas/particle velocity and temperature are being developed,
- Modelling of particle erosion has demonstrated the correct damage mechanism and erosion scar geometry.

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