METROLOGY TO ENABLE HIGH TEMPERATURE EROSION TESTING – A NEW EUROPEAN INITIATIVE

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ABSTRACT

The efficiency of high temperature energy generation plant and aero-engines is critically impacted by solid particle erosion, particularly at elevated temperatures. This damage process can reduce the efficiency of turbines by as much as 7 to 10%, and in the case of a large power plant cause an additional emission of 250,000 tonnes of CO_2 over the lifetime of the plant [1]. The cause and type of solid particle erosion varies across different industries and locations in plant, for instance the particles could be volcanic ash in aero-engines, fly ash in boilers, exfoliated scale in steam turbines or mineral matter in oil excavation. In all cases the performance of materials can be improved through better surface engineering and coatings, but the development of these is restricted due to lack of generic models, well controlled and instrumented tests and international standards. A framework is required therefore that can be applied to these different situations to characterise the high temperature erosion performance of new materials and coatings and thereby accelerate their development and design. To achieve this, a step change in the test methods and control of high temperature solid particle erosion is required. However, limitations in current measurement capability within this form of test prevent the advancement.

A new European initiative, METROSION, on the development of high temperature solid particle erosion testing has a primary aim to develop this metrological framework. Several key parameters have been identified for measurement and control; these include temperature (of the sample, gas and particles), flow rate, size and shape of the erodent, angle of incidence of the particle stream and nozzle design. This paper outlines the aims and objectives of this new initiative. With a particular focus on the techniques to be used for in-situ temperature, velocity and 3D shape/size measurements.

INTRODUCTION

In the last decade there has been increasing legislation requiring industry to cut and control carbon emissions that are believed to be linked to climate change. EC directives designed to limit CO_2 emissions and international treatise such as the Kyoto Protocol led the EU to commit to an 8% reduction in CO_2 emissions by 2008 – 2012 [2]. Whilst there are efforts to control and limit CO_2 emissions there is an increasing world energy demand [3]. As a consequence the power industry is actively seeking methods to capture and control the emissions. In fact the UK Electricity Market Reform (EMR) White Paper 2011 states that there should be "an Emissions Performance Standard (EPS) set at 450 g CO_2/kWh to reinforce the requirement that no new coal-fired power stations are built without CCS", which not only enforces the need for Carbon Capture and Storage (CCS) in new build but also imposes stricter limits on CO_2 emission than current EC directives. Whilst CCS is one method being developed, other alternatives are being pursued which include the retrofitting of existing plant and the conversion of coal fired plant to biomass combustion, either 100% or co-fired with coal. Whilst this will use a more carbon neutral fuel it does not eliminate the problem of erosion, and in the case of some biomass fuel will exacerbate the problem on the fireside components in boilers.

Erosion and wear can dramatically reduce the efficiency and life of high value components across a range of industrial sectors. In the European power industry this form of degradation alone costs an estimated 200M€ a year in lost efficiency, forced outages and repair costs [1]. In conjunction to a financial impact there is also a clear environmental impact from high temperature erosion, for example it has been estimated that reducing the erosion of the leading edge of turbine blades could result in improved efficiency, in the order of 7%, 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. Solid particle erosion at elevated temperatures is not only an issue for aerospace and power generation, but can also impact on heavy industry such as steel processing plants which can have issues from erosion in materials handling plant that causes major losses.

It is well documented that capture methods impact the efficiency of high temperature plant so using this method alone is not desirable; rather increasing the efficiency of plant through higher temperatures and pressures, improved materials and process control coupled with capture technologies is the route being pursued. Whilst increasing operating temperatures does increase the efficiency of the plant, current materials are at the limits of their performance. Higher temperatures are likely to lead to increased oxidation rates and exfoliation, thereby exacerbating the occurrences of high temperature solid particle erosion of components. Major improvements in the efficiency of power generating plant (7% to10%) and aero-engines will be made possible by the development of new materials that have improved resistance to high temperature particulate erosion. A recent EPRI (Electric Power Research Institute) survey [4] of High Temperature Solid Particle Erosion (HTSPE) testing exposed a serious deficiency within the EU to perform HTSPE 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 surface engineering solutions has been hampered by a lack of metrology and standardisation for issues such as the measurement of damage, the temperature of the erosive particles and the supporting gas stream, the gas stream flow rates, erosive particle size and shape. The lack of control of these parameters has been identified as the cause of a lack of reproducibility in measurements, up to 100%, by an EPRI workshop. There is a requirement to understand the variability in erosion measurements between different laboratories. Once this is clearly defined there will be sufficient understanding to develop a standard test procedure for HTSPE testing, which is currently not available, and enable advanced modelling for improved design routes and more accurate predictions of performance.

The implementation of improved in-situ measurement and rigorous characterisation of the erodent and the erosion scar will provide greater phenomenological understanding of the erosion processes at high temperature and the use of a more controlled test will enable better repeatability and reproducibility of testing. Without this necessary metrological framework, the development of new materials will still be based on a largely empirical approach that will significantly delay the improvements that are needed to meet the challenges of reducing environmental impact, and meeting the EU targets for CO_2 emissions.

Funding for this programme of work “METROSION” has been obtained through the European Metrology Research Programme (EMRP). This is a metrology-focused European programme of coordinated R&D that facilitates closer integration of national research programmes. The EMRP is jointly supported by the European Commission and the participating countries within the European Association of National Metrology Institutes (EURAMET e.V.), with the main aim to ensure collaboration between National Measurement Institutes (NMIs) thereby reducing duplication and increasing impact. Through this programme a consortium of National Measurement Institutes form the UK, Germany, Denmark and the Czech Republic has been formed to address the metrological challenges in developing a framework for HTSPE testing. Two leading research organisation from the UK and Italy have also been included in the consortium through Researcher Excellence Grants (REGs) to form the final METROSION consortium.

MEASUREMENT OF HIGH TEMPERATURE SOLID PARTICLE EROSION

A recent EPRI survey [4] of High Temperature Solid Particle Erosion (HTSPE) testing exposed a serious deficiency within Europe to perform HTSPE tests, with few facilities available worldwide for the measurement of high temperature particulate erosion. Within Europe facilities which met the EPRI requirement were principally located at Cranfield University (UK) and Ricerca Sul Sistema Energetico Spa, (IT), but even these test systems were limited in terms of the particle velocity and operational temperature required by the EPRI specification.

Outside of the EPRI programme and intercomparison described by Swaminathan *et al* [4], within the testing community it has been realized 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 measurement of the velocity of erodent particles is through a twin disc test system where rotating discs are used to give a measure of velocity. This method is generally considered to have measurement errors of the order of 20-30 % as described below.

Erosion is defined as a “progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multi-component fluid, or impinging liquid or solid particles” [5]. In determining the erosion rate of a particular system it is normally found that the rate increases with the exposure time, the most accurate method of determining this rate has been through the use of mass change, determined through periodic weighing of the specimens as a function of exposure time, although the erosion rate can also be measured by volume change. For accurate determination not only does the erosion rate need to be carefully determined but it is also critical to understand, measure and control the main parameters which influence the rate of erosion. This is strongly dependent on the material properties of the material being eroded as well as the following test parameters:

- Particle impact velocity
- Particle impact angle
- Particle size, shape and material
- Temperature

Particle Velocity

Perhaps the most important variable is the particle velocity, since under most conditions; it has a strong influence on the erosion rate. For many materials, once steady-state conditions have been reached the erosion E (expressed as the mass removed by unit mass of erodent particles) can be expressed [6] as a simple power function of particle impact velocity v.

$$E = kv^n \tag{1}$$

where the constant of proportionality k includes the effects of all the other variables. The value of n is the velocity exponent and is typically found to be between 2 and 3. The velocity exponent does not vary considerably with the impact angle although it is suggested that higher values of n can be due to impact angles close to perpendicular to the surface.

Particle velocity is difficult to measure accurately and requires advanced techniques, such as laser doppler velocimetry (LDV) or particle image velocimetry (PIV). The more traditional and widely used method of measurement is by using the double disc method popularised by Ruff and Ives [7]. In this method two disks are rotated on a common shaft, and the stream of erodent particles is arranged to strike the upper disk which has a thin radial slot cut in it (see Figure 1a). The lower disk is coated with a thin paint or dye film to show where particles strike it (see Figure 1b and c). Two erosion scars are formed: one with the disks stationary, with the particles passing through the slit in the upper disk, and the other with the disks rotating at a known speed. The angular displacement θ between the two scars is measured and can be used to calculate the time taken for the particles to travel the distance L between the disks, and hence their velocity, *v*. The velocity is given by

$$v = \frac{L\omega}{\theta} \tag{2}$$

where ω is the angular velocity of the rotating disks. In practical examples of this device a high rotational speed is needed to achieve reasonable displacement of the scars and thus accuracy of measurement of the angle θ. Values between 3,000 and 10,000 revolutions per minute are common, with a distance L of about 20 to 40 mm, according to test conditions. The method is well suited to use in a gas-blast erosion test, since velocity calibration can be carried out under exactly the same conditions of particle feed rate and air pressure as used in the erosion test. However, the random error in measuring velocity in this way is ±10% and there can also be a systematic error due to the aerodynamic influence of the rotating disks on the particle stream, which may be 10% or even greater for very small particles of low density.

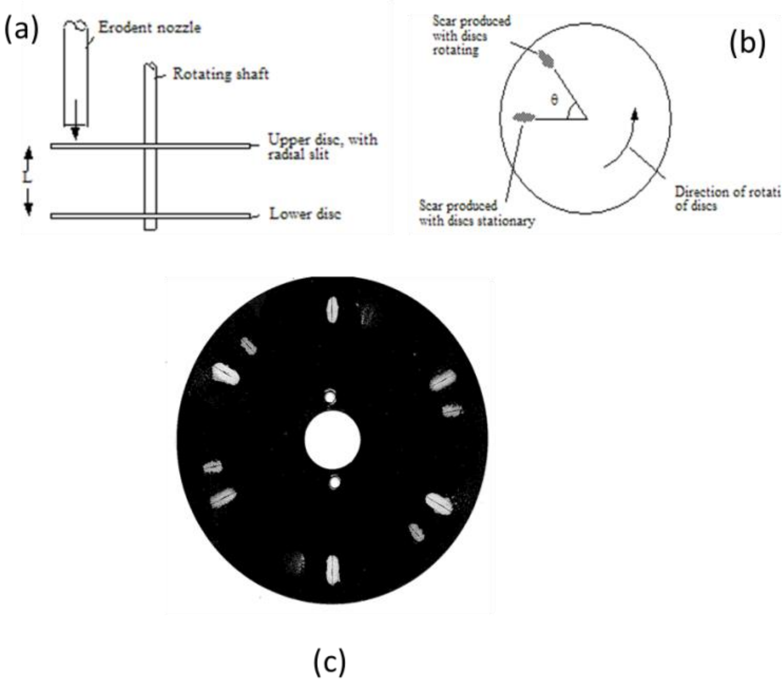

Figure 1 Schematic of the double disk particle velocity measurement showing (a) the side elevation of the apparatus, (b) the top elevation of the disk and (c) an image of a disk post exposure (Ref [6]).

An example data obtained from this method is shown in Figure 2, this shows how the velocity of particles varies with gas pressure. The data provides a good fit, but note how the intercept of the line does not pass through the origin. Whilst this data would appear to be good, and this is an example of a 'good set', this method in general has cumulative measurement errors of the order of 20-30 % leading to much greater uncertainty in the overall measurement. Moreover, the double disk method can only provide an estimate of the maximum particle speed achieved, but does not account for the velocity distribution which is dependent on particle size distribution, thus a significant spread in particle velocity is possible but unaccounted for.

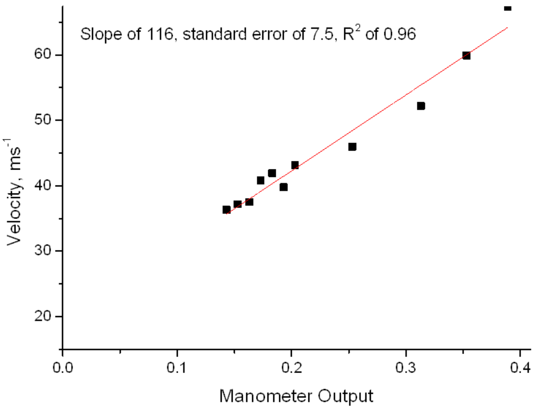

Figure 2 Variation of particle velocity as a function of gas pressure as measured using the double disk method.

Impact Angle

The impact angle in erosion is often defined as the angle between the direction of particle motion and the plane of the surface, such that a normal angle of incidence corresponds to an impact angle of 90°. Ductile materials eroded by angular particles show maximum erosion at shallow angles of incidence, with the peak erosion rate typically at an angle of 20 to 30°, Figure 3.

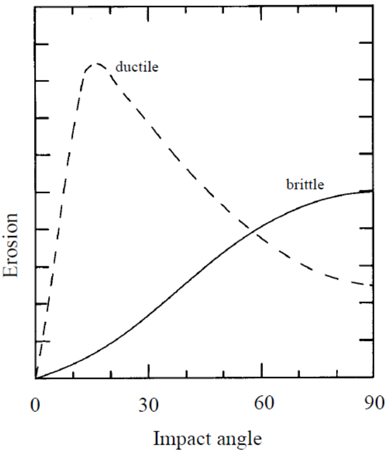

Figure 3 Typical dependence of erosion for different particle impact angle on different types of target material (Ref [6]).

Under these conditions the material is removed by a ductile ploughing and cutting mechanisms. The erosion of a ductile metal at 90° incidence may be about one half to one third of the peak value. Conversely materials which are brittle, such as ceramic coatings fail by the formation of brittle fractures and localized cracking. In these cases the maximum rate of erosion is found to occur for impact angles of 90°. For different erodents with different mechanical properties the erosion mechanism would not change but the extent of erosion would.

Particle Size and Shape

The particle size and size distribution are important parameters as these define the mass of erodent particles, and thus, together with the particle velocity, the kinetic energy of impact for erodent particles. This is further complicated when accounting for the contribution of the powder feed system, which could alter the size distribution through use. Moreover, depending on the nozzle geometry, particles can follow different trajectories depending on their size thereby affecting the erosion rate. For these reasons, it is clear that wherever possible the size range of the particles used in an erosion test should be known, and be as narrow as possible.

In normal situations the particles are often classified by a simple sieving operation [8]. Specification of the sieve sizes may be sufficient to define the range of particle size used in a test. In reality the size and distribution of erodent particles can vary as demonstrated by Figure 4.

The shape of the particles is also important in determining the relative erosivity of different particles [9], and is inherently difficult to separate from other properties, since particle shape is often determined by the fracture processes by which the particles themselves are formed. As in the case of particle size, there is an intrinsic effect of shape on the erosion rate, which can lead to angular particles producing up to ten or more times the erosion caused by spherical particles of the same material. Measurement of particle shape is not straightforward, since although there are many possible methods of assessing shape, it is unclear which method is most appropriate in the context of erosive wear testing. Qualitative descriptors such as “rounded”, “sub-angular” and “angular” etc, are often used and may be adequate in conjunction with a more detailed specification of the material and source of the erodent particles.

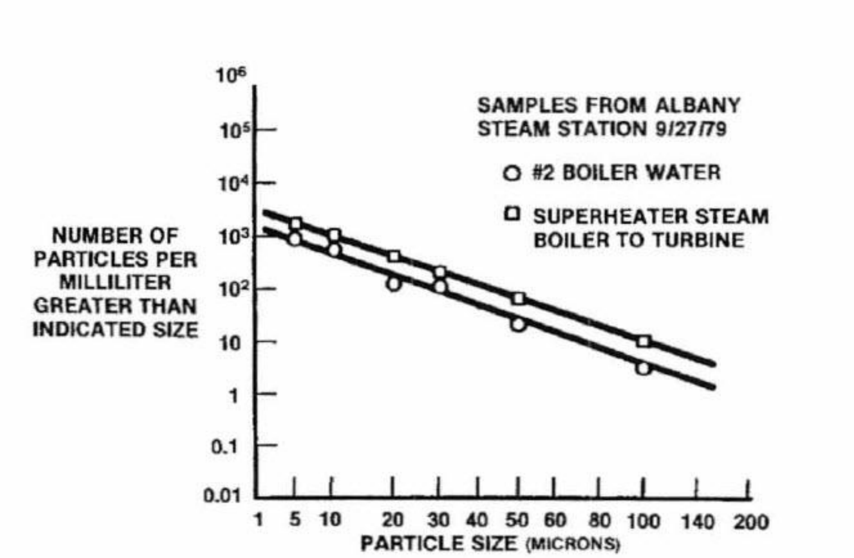

Figure 4 Particle size distribution of boiler scale recovered from boiler water and Superheater steam drains [4].

It is important that if the purpose of erosion testing is to compare material behaviour or obtain quantitative measurements of erosion rate in the context of a particular engineering application, appropriate erodent particles are used in the test. Not only should the particle size and shape be representative of the application in question but the particle material should also provide a realistic simulation of the properties of the actual particles. Figure 5 shows how the erosion rate varies as a function of impact velocity and erodent, for erodent particles of a similar size specification.

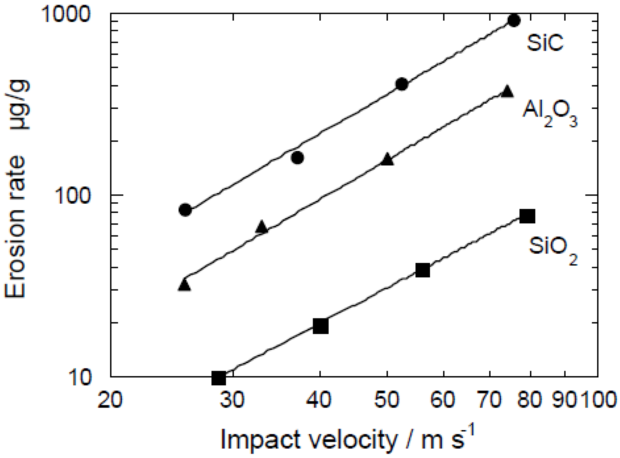

Figure 5 Influence of particle velocity and erodent material on the erosion rate of a sintered glass-bonded alumina ceramic, after Ref [9]

Temperature measurement is also critical in understanding and quantifying material performance. In current systems the temperature of the erodent particles is assumed to be the same as the gas stream, but even this temperature is not well defined as it is often measured in the heating system for the gas and not at the nozzle, leading to unknown uncertainties in measurement.

METROLOGICAL FRAMEWORK AND PLANNED ACTIVITIES

The aim of project is to take the measurement of erosion from solid particles at high temperature forward and significantly improve the measurement and control of key experimental parameters such that the test can be performed in a repeatable manner with known low levels of uncertainty. By measuring and controlling the test accurately a secondary aim is to monitor the erosion rate in-situ whilst the test is progressing and generate more generic models for high temperature solid particle erosion and validate them using the comprehensive data from the test. To enable these accurate measurements to be performed a number of advanced techniques will be needed to improve on the measurement and control of the parameters previously listed and described. To facilitate this there are four key technical activities.

- Selection of materials
- Test system construction, test parameter effect and modelling
- Measurement of volume, mass and shape
- Measurement of temperature, velocity and flow

Selection of materials

Materials are key foundation to the project, it is critical therefore that those used are carefully selected to ensure that, not only do they meet the requirements of the project but that they are relevant to the industrial stakeholders. To ensure this is the case a period of consultation is underway to gather information from the partners and stakeholders to gauge the range of materials, erodents and conditions of most interest. The final selection will consist of two substrates, relevant to high temperature applications, and four coatings, two of which will be chosen from the current leading coatings, with two new coatings developed by the project partners. This will give a set of 10 different materials combinations (two substrates, uncoated and four coatings). Also crucial will be the selection of four different erodents. These will include silica sand (Figure 6), aluminia (rounded and angular) and other industrially relevant erodents, such as fly ash. All the materials included in the programme will be thoroughly characterised.

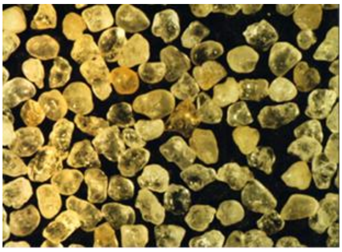

Figure 6 Example of shape distribution of silica erodent.

Understanding the effect of test parameters

To understand and quantify the uncertainties in the test it is important to fully quantify the effect of the various test parameters, such as angle of incidence (Figure 7), stand-off distance and nozzle aspect ratio. The effect these have on the erosion rate will be determined for different designs of apparatus, and the results used as the basis of a definition of an interlaboratory exercise that will be carried out with input from other international bodies such as EPRI and VAMAS.

Figure 7 Example of the effect of different angles of incidence in erosion testing.

Measurements to enable in-situ monitoring of erosion rates

This is a core activity that is concerned with the development and application of accurate methods for the measurement of the volume and mass loss through erosion, and to fully characterise the shape and size of the erodent particles. The aim is to be able to measure the volume change with a resolution of 1 μm^3 over a surface area of approximately 70 mm^2, and the mass change with an accuracy of 10 µg. The techniques to be used include mass loss measurements, optical methods of volume determination transferred from the earlier MADES project [REF], with a particular innovation being the development of new non-contact in-situ techniques based on laser scanning for real time volume measurement.

To aid as validation to the in-situ measurements, ex-situ volume measurements, based on optical techniques such as focus variation measurements using techniques developed in the EMRP MADES project will also be used alongside more traditional measurements using surface mapping by stylus profilometry.

A particular concern in these developments is that at high temperatures corrosion of many of the materials occurs simultaneously with erosion, and will have a major effect on the results of mass change measurements that are obtained. Erosion damage will cause a loss of mass, but high temperature corrosion will normally cause an increase in mass, providing there is no loss of material through spallation. This is a complex behaviour which varies with time and temperature, and so requires understanding for characterisation of long term materials performance. Procedures are required therefore for adjusting mass loss measurements to account for these changes; these will be based on secondary exposure tests without erosion conducted using thermogravimetric methods to measure the mass change with time and temperature due to high temperature corrosion.

In addition to monitoring the test specimen techniques are also required to evaluate the size, size distribution and shape of erodent particles. These key parameters have only been evaluated poorly in the past, but have a dominant effect on the magnitude of wear that occurs. For this purpose the use of industrial computed tomography (CT) as an emerging 3D coordinate measuring technology [10] will be investigated to determine the shape, size and size distribution of particles.

Having addressed the monitoring of the specimen during and after the test, it is also of crucial importance to monitor and control the dynamic test parameters such as temperature, velocity and flow. As a result there will be efforts to develop and apply accurate methods for the measurement of the velocity and velocity distribution of the erodent particles as they strike the test samples. As discussed previously techniques are available for velocity measurement which greatly improve on the double disk method, the accuracy and repeatability of these optical based techniques such as particle image velocimetry (PIV-S), particle shadowing and laser Doppler anemometry (LDA) will be assessed and compared with more traditional techniques such as the double disk technique.

The flow of the gas is inherently linked to the velocity of the erodent particle and will affect the spatial distribution of the erodent particles. The flow of the gas will additionally impact on the temperature of the system, therefore it is also necessary to develop and apply accurate methods for the measurement of the gas flow and temperature of the samples, the erodent particles, and the gas. Although the measurement of the sample temperature is relatively straightforward, care is still needed to ensure that appropriate methods are available to monitor the variation of temperature across samples and understand any heat flux effects through the sample thickness, this can be important depending on where the reference temperature measurement is being made. High speed thermal imaging of the sample surface will be considered as an appropriate technique for the sample. The measurement of the temperature of the high velocity erodent particles is more challenging. However, it is essential that robust measurement techniques are developed as it is essential that the temperature of the erodent is the same temperature as the sample to achieve high quality erosion measurements.

To date little modelling of long term performance of the high temperature erosion process has taken place [11], so that prediction of material life-time is very uncertain. Currently, empirical models exist for predicting solid particle erosion but by their very nature, these models are heavily dependent on experimental data in the form of erosion coefficients. These models are suitable for predicting erosion rates in well-defined situations where a wealth of experimental data already exists. They are useful in comparative work e.g. material ranking. If modelling of a more general erosion process or a more complex geometry is required, the empirical models are no longer applicable.

The limitation on the applicability and development of predictive models to date has been the lack of well-defined interactions between the erodent and the surface. The metrological framework outlined above will facilitate the delivery of these critical input parameters and physical understanding. This will ultimately be realised in a new high temperature solid particle test apparatus which will be able to perform and monitor these tests in a much more controlled and accurate manner than previously possible.

CONCLUSIONS

Current methods of measurement and control of test parameters, such as particle velocity, are known to have large uncertainties attached to them, leading to variability and imprecise evaluation of erosion performance at high temperature. An approach to improve the measurement of the key test parameters and the development of in-situ monitoring of erosion damage has been outlined as part of a new European initiative METROSION. To achieve the aims of the project the following technical and scientific objectives are to be met:

- Measurement of the volume of erosion through in-situ sensors, capable of measuring depth of damage to a resolution of 1 μm^3 enabling on-line measurement of the erosion rate.
- In-situ measurement of the velocity of high temperature erodent particles and its distribution.
- High speed measurement of the temperature of high velocity erosive particles and the supporting gas stream at temperatures up to 1000 °C.
- Measurement of the gas stream flow rate and its distribution.
- Measurement and characterisation of the erosive particle size and shape, and consequentially their respective speeds.
- 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 the results.

An outline of the approaches to be adopted has been presented for the key parameters, measurement of these will allow for the evaluation of the uncertainty in HTSPE tests to be made and through the use of improved techniques and test control the uncertainty will be reduced.

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