

APPROACHES TO MODELLING FIRESIDE CORROSION OF SUPERHEATER / REHEATER TUBES IN COAL AND BIOMASS FIRED COMBUSTION POWER PLANTS

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ABSTRACT

The combustion of coal and biomass fuels in power plants generates deposits on the surfaces of superheater / reheater tubes that can lead onto fireside corrosion. This type of materials degradation can limit the lives of such tubes in the long term, and better methods are needed to produce predictive models for such damage. This paper reports on four different approaches that are being investigated to tackle the challenge of modelling fireside corrosion damage on superheaters / reheaters: (a) CFD models to predict deposition onto tube surfaces; (b) generation of a database of available fireside corrosion data; (c) development of mechanistic and statistically based models of fireside corrosion from laboratory exposures and dimensional metrology; (d) statistical analysis of plant derived fireside corrosion datasets using multi-variable statistical techniques, such as Partial Least Squares Regression (PLSR). An improved understanding of the factors that influence fireside corrosion is resulting from the use of a combination of these different approaches to develop a suite of models for fireside corrosion damage.

INTRODUCTION

The combustion of solid fuels in power plants currently results in the generation of ~35-40% of the electricity used around the world [1]. Coal and biomass combustion are complex processes, with the minor and trace compounds from these fuels generating a range of chemical species whose composition and quantity depend upon the initial fuel chemistry [2-6]. As these species pass through the boilers they continue to react and can generate deposits on the fireside surfaces of superheater/reheater tubes. As well as fly-ash particles these deposits often contain sulphate, chloride and carbonate species. A combination of such deposits with the local flue gas and gas/surface/metal temperatures can result in a form of deposit-induced corrosion known as fireside corrosion. This is one of several degradation mechanisms that can limit the lives of superheater/reheater tube materials during long term usage. Key steps in developing advanced solid fuel fired power generation systems (to increase future power generation efficiencies and cut environmental emissions) are to model alternative degradation mechanisms to enable the selection of appropriate materials and operating conditions to give longer component lives [3-7].

Many different methods have been used to assess the extent of damage inflicted on heat exchanger materials systems by specific operational conditions and fuels [6-13]. The data generated in various laboratory fireside corrosion tests have frequently been used to rank alloys. However the exposure conditions used often produce damage that does not reflect that found in plants (even

allowing for the accelerated damage conditions that have to be used in most laboratory exposures) and the materials assessment methods do not produce data that can be used for quantitative modelling of materials damage.

This paper reports on a series of different approaches that are being used to tackle the challenge of modelling fireside corrosion damage on heat exchangers:

- Development of CFD models to enable the prediction of deposition onto tube surfaces using different potential particle and vapour deposition mechanisms.
- Inclusion of fireside corrosion data in a database of materials information that is being generated to support the development of coal and biomass fired power generation systems.
- Development of mechanistic and statistically based models of fireside corrosion from laboratory exposures and dimensional metrology.
- Statistical analysis of plant derived fireside corrosion datasets, e.g. multi-variable statistical techniques, such as “Partial Least Squares Regression”

Improved understanding of factors influencing fireside corrosion is resulting from the use of a combination of different approaches to develop a suite of models for fireside corrosion damage.

DEPOSITION ON SUPERHEATER / REHEATER TUBES

During the combustion of coal and biomass the reactions of the extraneous and inherent mineral matter in the fuels results in the release of ash particles of varying sizes and vapors of alkali species [2,14,15]. Solid ash particles can deposit according to a variety of mechanisms, but for heat exchanger tubes these are principally direct inertial impaction, eddy impaction and thermophoresis. Vapors can condense homogeneously in the gas phase or heterogeneously on solid particles and directly on heat exchanger / deposit surfaces. The build-up of deposits on heat exchanger tube surfaces partially insulates them from the flow of the hot combusted gas stream and reduces heat transfer between this gas stream and the steam coolant flowing within the tubes, thus raising the deposit surface temperature.

Computational Fluid Dynamics (CFD) has been used to study the flow of gases and particles around heat exchanger tubes and predict deposition via different potential mechanisms (particle impaction, thermophoresis and vapour condensation) [14]. This work used an Eulerian-Lagrangian model to describe the gas flow field around tubes and the solid ash particle trajectories respectively. User Defined Functions (i.e. UDFs) were developed for the CFD software package (ANSYS Fluent) to enable the prediction of the variation in deposit growth, deposition fluxes and temperature gradients through the deposits formed around superheater / reheater tubes.

The model developed has been applied to different geometries that could also be experimentally investigated in a small (100 kW_{th}) pulverized fuel combustion pilot plant. Figure 1 shows part of the mesh that was used for the CFD calculations using one of the probe configurations investigated (a triangular array of tubular probes). A triangular mesh was chosen to enable predictions of the dynamic growth of deposits to be carried out in later work. Following measurements of fly ash samples collected during the experimental work, the particle diameters used for the modelling were set by a Rosin Ramler distribution with a minimum (d_{\min}) = 0.43 μm , mean (d_{mean}) = 68 μm and maximum (d_{\max}) = 535 μm . In calculating the deposition fluxes, following a sensitivity analysis, an alkali sulfate vapour level of 1 ppm was used for the example model application reported in this paper. Figure 2 shows the flows of particles through this array of probes and illustrates the behavior of different size particle; a greater proportion of smaller

particles are present in the wakes of the two downstream probes, but larger particles rebound off the upstream surfaces of these probes (increasing the flux of these particles onto the downstream surface of the most upstream probe). Figure 3 shows the predicted variation in overall deposition fluxes around the three probes.

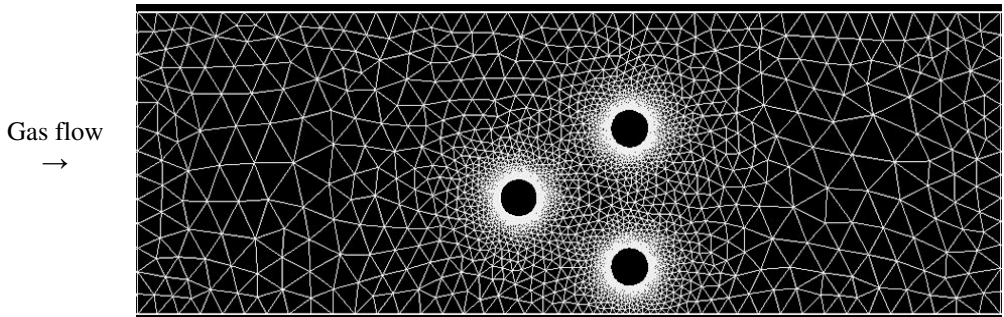


Figure 1 Example of part of the CFD mesh used for one of the tube configurations investigated within the combustion test rig (combustion chamber width = 300 mm, tube diameters = 39 mm)

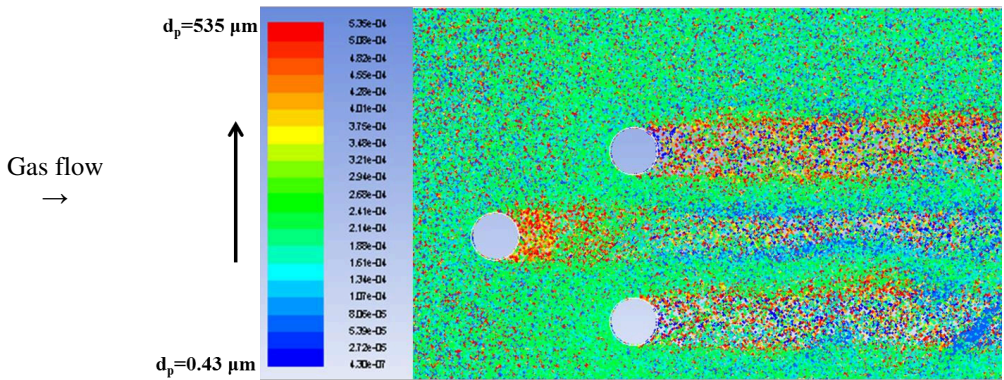


Figure 2 Example of model predictions of ash particles tracking through the triangular probe array: probe diameter (d_t) = 39 mm; ash particle sizes given by Rosin Ramler distribution with $d_{min} = 0.43 \mu\text{m}$, $d_{mean} = 68 \mu\text{m}$, $d_{max} = 535 \mu\text{m}$; polydispersity parameter $n = 1.07$; inlet gas velocity = 2 m/s.

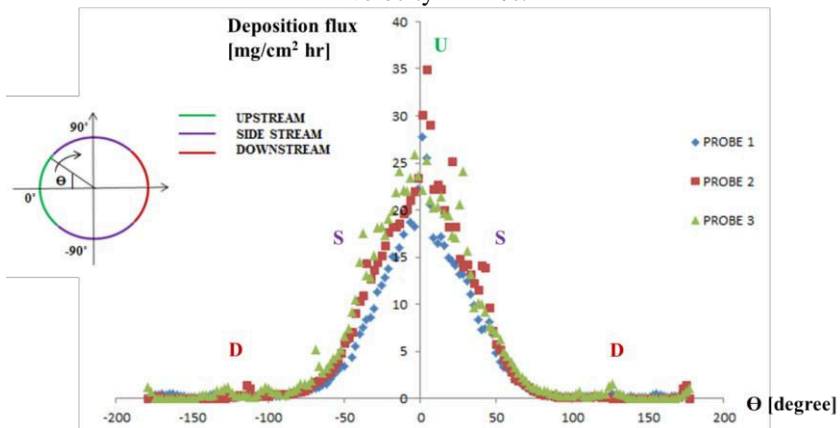


Figure 3 Predicted deposition fluxes around probes in triangular array (using a surface temperature of 773 K and exposure conditions given in Figure 2)

The predictions generated by the CFD models developed have been compared to experimental deposition flux data generated during the exposure of cooled probes in a small (100 kW_{th}) pulverized fuel combustion pilot plant to an environment generated by the combustion of UK Daw Mill coal co-fired with 12 wt % miscanthus. Figure 4 shows a comparison between these experimentally determined deposition fluxes and the modelling predictions; for comparison predictions based on other alternative models have been included in this figure.

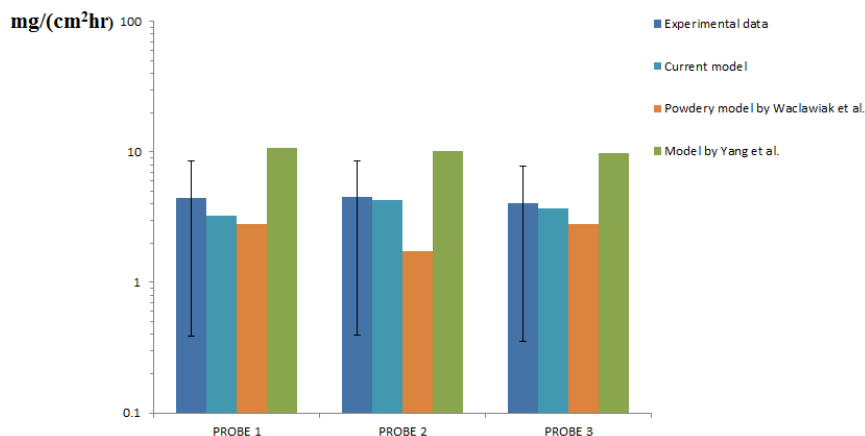


Figure 4. Comparison of the total deposition fluxes between the experiments and several sticking models on ceramic probes (773 K, $d_r=39$ mm) using the 1st probes' configuration ($U_0=2$ m/s, $d_{min}=0.43$ μ m; $d_{mean}=68$ μ m; $d_{max}=535$ μ m; polydispersion parameter $n=1.07$) [14,16,17]

The CFD deposition model is currently being further developed to enable the change in shapes of the deposits during exposures to be predicted more easily and allow the mesh used in the model to be continuously updated to reflect these changes.

HEAT EXCHANGER MATERIALS DATABASE INCLUDING FIRESIDE CORROSION

A database is being developed for the materials information needed to enable the design of combustion power plants with metal temperatures of up to 800 °C. This development started as part of a recent EU project [18,19] with the recognition that there was some data available, but that it had mostly been generated in isolated research activities and so was somewhat disjointed. Thus, the intention behind the development of this database was to systematically gather together appropriate data from the open literature and project partners; with the database covering specific alloy mechanical properties (e.g. creep, low cycle fatigue), physical properties (e.g. thermal expansion and conductivity) and environmental degradation (e.g. fireside corrosion and steam oxidation). Figure 5 schematically shows the structure of the database, focusing on fireside corrosion and steam oxidation examples. A critical part of this database development is consideration of the quality of the available data in terms of the exposures carried out, data generated and materials used (including sources, compositions, surface finishes, heat treatments).

For fireside corrosion, the quality of the available data can range from that generated in terms of metal loss distributions using well-characterised environments and standardised test methods, to weight change data from less defined exposure conditions. Figure 6 illustrates the level of detail required for the example of laboratory fireside corrosion datasets in terms of the exposure conditions. In addition, this compiled dataset enables the identification of areas of weaknesses in currently available data which need to be addressed. Much of the data that is openly available is

of low quality and so there needs to be targeted generation of more appropriate data from a range of different exposure conditions (and thorough reporting of the details of the data generated).

The gathering of such quantitative data on materials degradation enables a more robust overall dataset to be produced, and will facilitate the future development/validation of improved models and also reduce the risks involved in materials selections.

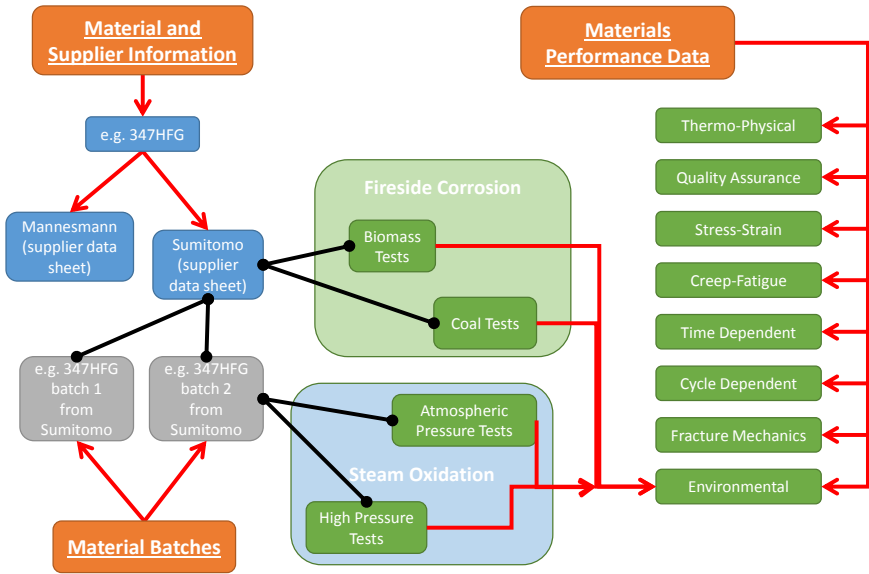


Figure 5 Schematic diagram showing the structure of the developing database [18,19]

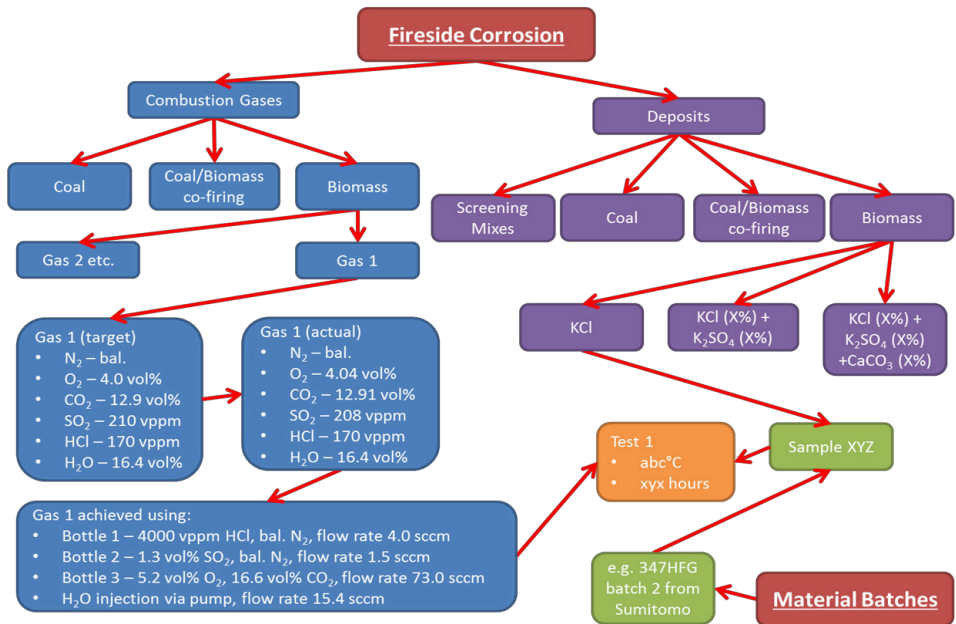


Figure 6 Schematic diagram showing the level of detail required for reporting of laboratory based fireside corrosion exposures

FIRESIDE CORROSION – DATA AND MODELS FROM LABORATORY EXPOSURES

The use of laboratory exposures enables key degradation parameters (e.g., gas composition, deposit composition and flux, metal temperature and time) to be systematically varied and closely controlled. This has enabled the development of a much better understanding of the effects of these variables (and their interactions) on fireside corrosion; Figure 7 [2] illustrates the effects of deposition flux, SO_x level and temperature on the propagation stage of fireside corrosion. However, to obtain results in viable exposure times, laboratory exposure need to be accelerated relative to plant exposures, and assumptions need to be made about the exposure parameters that are important in producing fireside corrosion damage; thus there is a need to better understand the development of this type of damage.

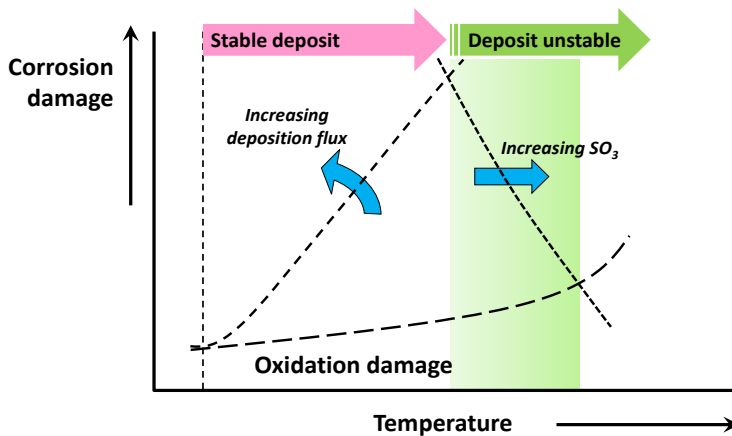


Figure 7 Schematic representation of key factors related to the fireside corrosion peak encountered on superheaters/reheaters in coal combustion systems and the effect of changes in exposure conditions [2]

The fireside corrosion exposures have been carried out using the well-established ‘deposit recoat’ test method, which is described in detail elsewhere [10,20,21]. This uses alumina-lined vertical controlled-atmosphere furnaces that can each accommodate 24 samples at a time in individual alumina crucibles [e.g. 9]. Tests were carried out at 600, 650, 700, 750 and 800 °C for periods of up to 1000 hours, with deposit re-coats every 200 hours. For this paper, data have been selected from aggressive deposits used to accelerate fireside corrosion simulating degradation caused by the combustion of two types of fuels: (1) coal using a deposit of $\text{Na}_2\text{SO}_4/\text{K}_2\text{SO}_4/\text{Fe}_2\text{O}_3$ with a molar ratio of 1.5/1.5/1 (often used as a screening deposit in UK/EU research programs [2,6,12]); and (2) biomass using a deposit of KCl. In both cases the deposit compositions can change during the exposures depending on the exact reaction conditions. The materials exposed included: a ferritic/martensitic steel (T92, only at the lower temperatures), austenitic steels (347HFG, 304H, 316L, Sanicro 25) throughout the temperature range, and Ni-based alloys (740H, 263, 617) at the high temperatures. A key part of this work was to use dimensional metrology before and after sample exposures to generate distributions of metal losses and any internal corrosion damage for all of the samples and exposure conditions investigated [10,19-21].

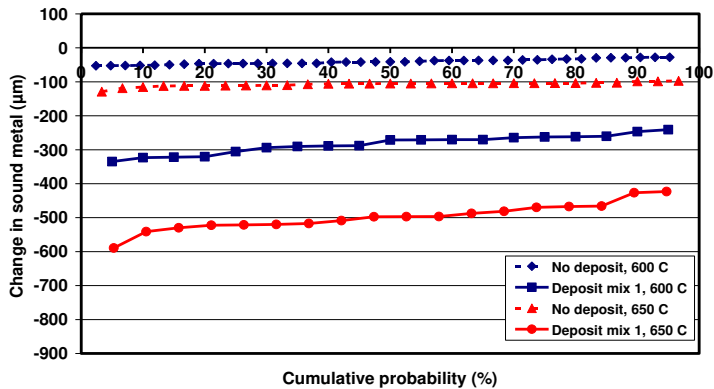


Figure 8 Examples of ‘change in sound metal’ distributions for T92 with and without alkali iron sulphate deposits exposed in simulated air-fired coal combustion gases for 1000 hours at 600 and 650 °C [21]

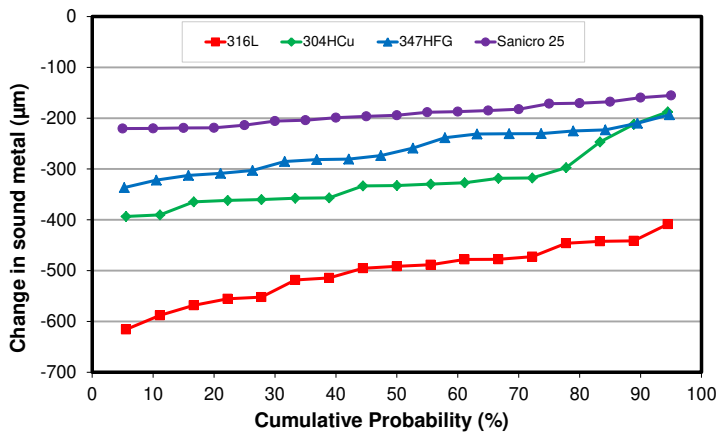


Figure 9 Austenitic alloys with an alkali iron sulphate deposit in simulated air-fired coal combustion gases for 1000 hours at 650 °C in an accelerated fireside corrosion exposure [22]

FIRESIDE CORROSION – STATISTICAL ANALYSES OF PLANT DATA

Fireside corrosion data obtained from power plant exposures are useful in terms of the evaluation the morphologies of corrosion damage obtained from particular exposure environments and metal temperature ranges [6,20,23]. Quantitative data for damage is also necessary for testing mechanistic models generated from laboratory exposures. However, the limitations of many plant datasets need to be recognized in terms of variations in exposure condition with time (such as plant cycling), fuel changes, metal temperature variations [6]. In addition, the results of such exposures are often reported in terms of average or maximum damage, rather than giving an indication of the distribution of damage obtained; however, some more recent long-term exposures of probes in power plant boilers has generated distribution of metal losses as a function of temperature and alloy for particular exposure locations [7,8,16,20,23].

This activity has focused on using existing fireside corrosion data (obtained in a series of studies in plants within the UK and US [7,8,23]) as a basis for an investigation of the potential of using statistical analysis of the data to generate models to predict the fireside corrosion damage of superheater and reheater materials. Inputs include alloying elements, fuel compositions and operating temperatures (local gas and metal surface temperatures). The feasibility of using two multivariate statistical techniques have been investigated: principal component regression (PCR)

and partial least squares regression (PLSR). Both of these techniques reduce the dimensionality of the datasets and identify the key input parameters in each dataset necessary to generate predictions of fireside corrosion rates. They differ in the methods used in extracting the latent variables that define their reduced dimensional spaces. PCR produces a weight matrix reflecting the covariance structure between the predictor variables (X_i), while PLSR produces a weight matrix reflecting the covariance structure between the predictors (X_i) and response variable (Y) [24]. It should be noted that, unlike the work described in earlier sections of this paper, this approach deliberately does not include consideration of physical and chemical mechanisms for combustion, deposition or corrosion, or the microstructures of tube materials.

Several potential framework models have been evaluated during the course of this activity using both PCR and PLSR methods. It was found that PLSR generally gave the most reliable results and selected the fewer number of significant variables, with the best performing framework model being:

$$\ln CR = \ln \beta_0 + \beta_1.1000/T_m + \beta_2.\ln(T_g-T_m) + \beta_3.\ln a_1 + \beta_4.\ln a_2 + \dots \beta_k.\ln f_1 + \beta_{k+1}.\ln f_2 + \dots + \varepsilon$$

where, CR is corrosion rate ($\mu\text{m}/\text{hr}$), T_m is metal surface temperature (K), T_g is local gas temperature (K), a_i are alloy composition elements (%), f_i are fuel composition elements (%), ε is standard error and β_i are the coefficients determined for each significant variable.

Examples of outputs of these models are presented in Figure 10 for datasets obtained for the corrosion of austenitic steels in pulverized fuel power plants fired on UK coals, US coals and UK biomass.

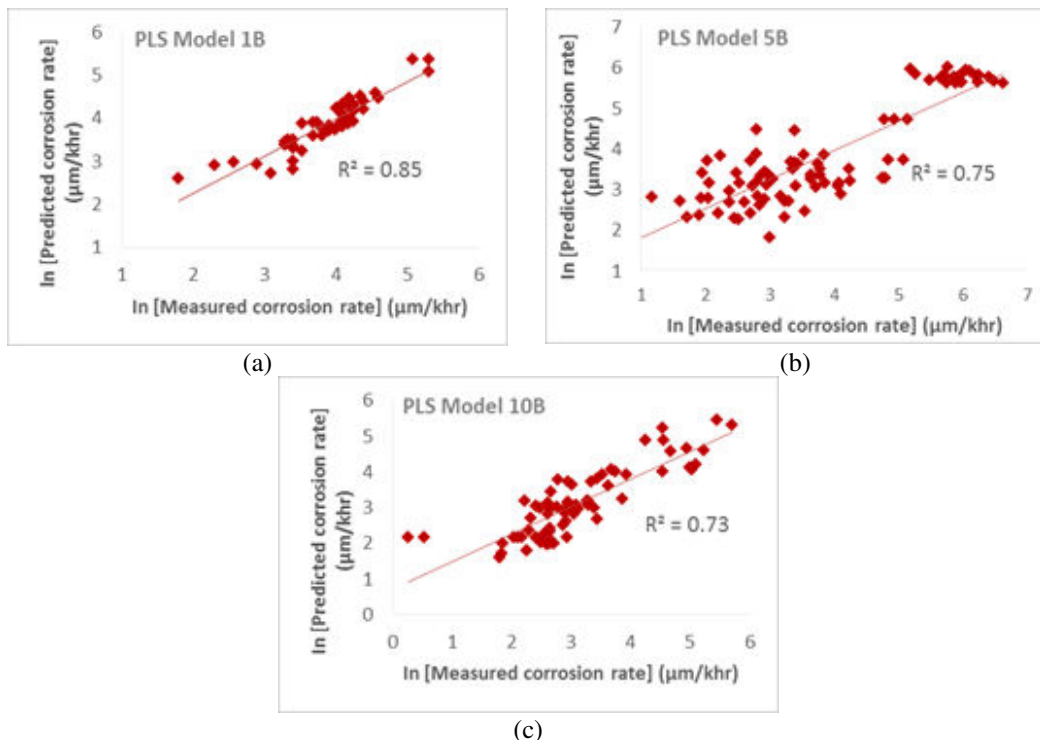


Figure 10 Examples of PLSR applied to fireside corrosion data generated from exposure of austenitic alloys in power plants fired using examples of (a) UK coals and (b) US coals and (c) biomass fired in UK [23]

CONCLUSIONS

This paper has summarized four different approaches that are being investigated to tackle the challenge of modelling fireside corrosion damage on superheaters / reheaters:

- CFD models to predict deposition onto tube surfaces.
- Generation of a database of available fireside corrosion data.
- Development of mechanistic and statistically based models of fireside corrosion from laboratory exposures and dimensional metrology.
- Statistical analysis of plant derived fireside corrosion datasets using multi-variable statistical techniques, such as Partial Least Squares Regression (PLSR).

As consequence of using a combination of different approaches to investigate the development of a suite of models for fireside corrosion damage, an improved understanding of the factors that influence fireside corrosion is being generated.

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