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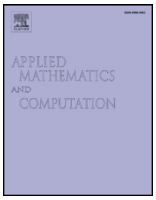

Design and optimisation of the nozzle of an innovative high temperature solid particulate erosion testing system using finite element modelling

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ABSTRACT

A new high temperature solid particulate erosion test system has been designed at the National Physical Laboratory 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}. This has been achieved through the careful design of the nozzle, balancing the gas flow, gas pressure and nozzle geometry to achieve the design goals. The nozzle design has been carried out using multi-physics Finite Element Modelling to analyse the gas flow and temperature.

1. Introduction

The efficiency of high temperature energy generation plant and aero-engines is critically impacted by solid particle erosion, particularly at elevated temperatures. 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 [1]. The long-term industrial aim is to be able to develop high temperature systems where the components are manufactured from appropriate materials, the materials degradation modes are identified and that models exist to predict material performance [2].

For many years high temperature particulate erosion (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, 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 (Electric Power Research Institute) workshop [3].

There are currently few facilities available worldwide for the measurement of high temperature particulate erosion. Those that exist are limited in terms of the particle velocity and temperature. A new European initiative on the development of high temperature solid particle erosion testing has a primary aim to develop the metrological framework necessary to fully

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instrument and monitor high temperature solid particle erosion testing. 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 [4].

As part of this initiative, a new high temperature solid particulate erosion test system has been designed at the National Physical Laboratory (NPL) to extend the capability 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}. This has been achieved through the careful design of the nozzle, balancing the gas flow, gas pressure and nozzle geometry to achieve the design goals.

The nozzle design has been carried out using multi-physics Finite Element Modelling (FEM) to analyse the gas flow and temperature. The advantage of using multi-physics FEM/computational fluid dynamics (CFD) type packages are that they give a quantitative insight into erosion dynamics both numerically and visually. This gives engineers the ability to modify designs rapidly and inexpensively, such as the continuous improvement of erosion rigs [5] or designing to reduce erosion of, for example, control stage nozzles in supercritical stream turbines [6,7].

In this current work we have concentrated on predicting the flow of gas only through the nozzle. This simplifies the design process as only a continuous flow field simulation is required. In these simulations the flow can be treated as the continuum phase, the motion of which is determined by solving the Reynolds averaged Navier–Stokes (RANS) equations. The resulting flow field is a description of the velocity of the fluid at a given point in space and time. Navier–Stokes equations describe the motion of fluid based on conservation of momentum equations therefore other equations, such as conservation of mass, conservation of energy and wall conditions, are also needed to define the flow field. The standard no-slip wall function is commonly used [5,8,9]. The use of RANS equations supplemented with turbulence models allow turbulent flow to be included and the standard k-ε turbulence model is often used [5,7,10], although there are a range of other k-ε turbulence models available. The convenience of the standard k-ε turbulence model is that it doesn't require a fine mesh near the walls [11].

2. The design process using FEM

In designing the nozzle, there were several key issues that had to be considered: the required main gas stream inlet pressure and powder feeder gas pressure to achieve the target speed at the outlet (300 ms^{-1}), at the required temperature (900 °C); the location of the powder feed along the nozzle; the diameter of the nozzle exit; the length of the nozzle; the lining of the nozzle; and ease of manufacture.

An extensive period of design using FEM was conducted to optimise the nozzle geometry. For all of the models developed a commercially available FEM package, COMSOL Multiphysics$^{\mathrm{TM}}$ 4.4 (COMSOL AB, Stockholm, Sweden), was used to perform the numerical simulations.

Other hot temperature erosion rigs, such as those at RSE (Ricerca sul Sistema Energetico, Italy) and CU (Cranfield University, UK) [3,12], partners of the project, have a coil which sits inside a furnace, or a labyrinthine pressure system to heat up the gas from room temperature to the required temperature. Based on this, in the first instance, a heat transfer model was set up to calculate the length of the pipe or coil needed for the gas to reach 900 °C, without including the nozzle. This model predicted the temperature of the gas within the pipe, and the results showed that approximately 100 m of a 5 mm internal diameter (ID) pipe were needed for the gas to reach 900 °C when the furnace was heated to 1100 °C. This figure is of a similar length as the coil in the RSE rig (who report that a length of 70 m is needed to heat up the gas to 950 °C). A limitation of this approach was that it was too simplistic, as it did not take into account any pressure drop or variation in the speed of the gas. In practice there were too many unknowns (pressure, temperature and speed at the inlet and outlet) to fully account for these and thus for a better understanding of the whole process a coupled model of pipe and nozzle was needed.

As a consequence a model which included the pipe or coil connected to the nozzle was developed and validated using experimental data from the RSE apparatus which was available for room temperature and 430 °C. However, the agreement between the model and the experimental data was not as good as anticipated and it became clear that there was insufficient experimental data to fully understand where the discrepancies originated, and whether the model predictions were correct or incorrect. One of the main problems was believed to be due to the very large pressure drop between the coil entrance and the nozzle exit necessary to ensure the gas exiting the nozzle was at the target speed. Therefore other options to heat the gas were investigated.

An alternative approach to having a long coil inside a furnace to heat up the gas was the use of a commercial air heater. This is a compact off the shelf item, which can deliver air at the required temperature of 900 °C, which connects directly to the nozzle with no need for a pipe system to heat up the gas, hence avoiding the problems of having a large pressure drop. This approach offers a simple method for heating the gas to any required temperature. The chosen air heater has an outlet flange of 92 mm, necessitating the use of a cone to funnel the air from the heater outlet down to the nozzle inlet, Fig. 1.

Having established a method to heat the incoming air stream, the next step was to design a nozzle to fit onto the air heater. The air heater outlet of 92 mm is the nozzle's inlet ID, with this funnelling down to the 'throat' ID. Having a 'throat' section, which has an ID smaller than that of the outlet section increases the velocity of the gas. The outlet diameter of the nozzle was fixed at 5 mm, and a length of 200 mm was chosen for this section which was shown to be long enough for the gas and particles to reach laminar flow conditions. This aspect ratio (length/diameter) fits with the ASTM standard [13] which suggests that a length/diameter ratio of at least 25 is desirable to achieve an acceptable particle velocity