

Parametric Study on Erosion Rig Nozzle

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SUMMARY

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 m/s. This was achieved through the careful design of the nozzle, balancing the gas flow, gas pressure and nozzle geometry to achieve the design goals.

The nozzle model has been extended to include the sample and air within the erosion rig chamber to allow predictions of the gas exiting the nozzle and impacting the sample. The model for this nozzle and an alternative nozzle designed by Ricerca sul Sistema Energetico (RSE) have been used to run parametric studies to investigate the effect of temperature, inlet pressure, stand-off distance and impact angle on the gas velocities reaching the sample. The results have also been compared to complimentary modelling work involving predicting the erosion caused by a single particle impact.

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CONTENTS

1.	INTRODUCTION	1
2.	FE MODELS	2
2.1	NPL NOZZLE	2
2.2	RSE NOZZLE	5
2.3	SINGLE PARTICLE IMPACT MODEL	6
3.	PARAMETRIC STUDY DETAILS	7
4.	PARAMETRIC STUDY RESULTS	7
4.1	EFFECT OF TEMPERATURE	7
4.2	EFFECT OF INLET PRESSURE	11
4.3	EFFECT OF STAND-OFF DISTANCE	14
4.4	EFFECT OF IMPACT ANGLE	19
5.	CONCLUSIONS	29
6.	REFERENCES	30

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 develop a system 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 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 or 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 the NPL nozzle model has been extended to include the sample and air within the erosion rig chamber to allow predictions of the gas exiting the nozzle and impacting the sample. The model for this nozzle and an alternative nozzle designed by RSE (Ricerca sul Sistema Energetico, Italy) have been used to run parametric studies to investigate the effect of temperature, inlet pressure, stand-off distance and impact angle on the gas velocities reaching

the sample. Where applicable the results have also been compared to complimentary modelling work involving predicting the erosion caused by a single particle impact.

2. FE MODELS

2.1 NPL NOZZLE

The NPL designed nozzle is shown in Figure 1. The nozzle has an outlet flange of 92 mm to enable attachment to the commercial air heater, used to heat up the gas before the gas enters the nozzle. The nozzle then funnels down to the 'throat'. Having a 'throat' section, which has an inner diameter 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 [8] which suggests that a length/diameter ratio of at least 25 is desirable to achieve an acceptable particle velocity distribution in the gas stream. The model includes a pressurised and heated (up to 60 °C) powder feeder. The angle of incidence of the powder feeder was 30° as this gave a smooth flow transition into the main body of the nozzle. The powder feeder connects after the throat constriction so that the powder does not clog up in the throat section. The powder line length was chosen to ensure that the powder is warm enough so that the presence of the powder does not cool the gas once it joins the main gas stream.

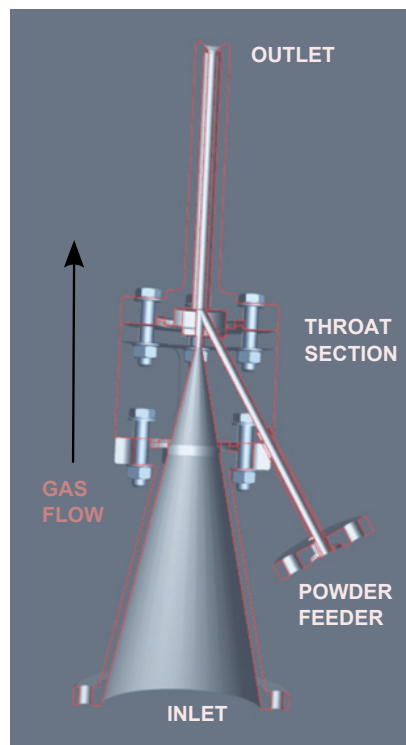


Figure 1: Schematic 2D cross-section of the final nozzle design showing the air feeder cone.

A 2D axis-symmetric model was used as a representation of the 3D nozzle to reduce computational costs. The gas inside the nozzle was modelled using a non-isothermal flow model. The fluid flow solution was obtained by solving the Reynolds Averaged Navier-Stokes (RANS) equations, which were coupled to the heat equation to account for the non-isothermal flow. A k - ϵ turbulence model was used to capture the effect of turbulence on the fluid flow. The gravity forces on the gas flow were neglected, and steady-state flow was studied. Along the nozzle walls, turbulent wall functions were assumed to be the flow boundary condition and a heat exchange with the furnace was used as the temperature boundary condition. At the nozzle inlet fixed pressure and temperature conditions were imposed, and at the outlet a fixed pressure (atmospheric) and an outflow temperature condition were used. Details of the equations used in the model can be found in [9]. Boundary conditions at the powder feeder inlet were imposed: a fixed pressure at the powder feeder inlet and a fixed temperature (60 °C); on the walls of the powder line, turbulent wall functions were imposed for the flow and for the temperature a heat flux exchange with the exterior furnace.

To account for the asymmetry of the particle feeder with respect to the nozzle, as can be seen in Figure 1, a particle feeder of reduced diameter was used for the 2D axis-symmetric model, such that when rotated its cross-sectional area would be equivalent to that of the original particle feeder in 3D, Figure 2.

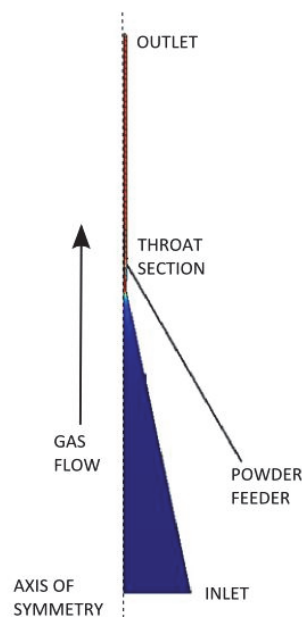


Figure 2: 2D axis-symmetric geometry used within the model, with reduced diameter powder feeder.

This model has been extended to include the sample and the surrounding air within the erosion rig chamber, see Figure 3. Within COMSOL a two-step approach was used within the turbulent flow module. Step 1 solves the nozzle model only (Figure 2) using the pressures at inlet and outlet as boundary conditions. Step 2 solves the air region plus a short section of the nozzle, and uses the velocity at the boundary from step 1 as the inlet condition to step 2. The following settings for the turbulent flow physics and solver were used: no inconsistent stabilization, standard turbulent model parameters, absolute pressure, pA set at 1 atm with a segregated solver.

Initial conditions for the model were:

- Temp 900 °C (assuming it is all at that temperature) and sitting in a furnace at 1000 °C
- Pressure at the inlet of the nozzle and of the powder feeder 1.3 bar
- Stand-off distance 16 mm
- Sample width 25 mm
- Radius air region 100 mm

The velocity predictions for this model are shown in Figure 4 as a swept contour plot i.e. axisymmetric model rotated to give a 3D image.

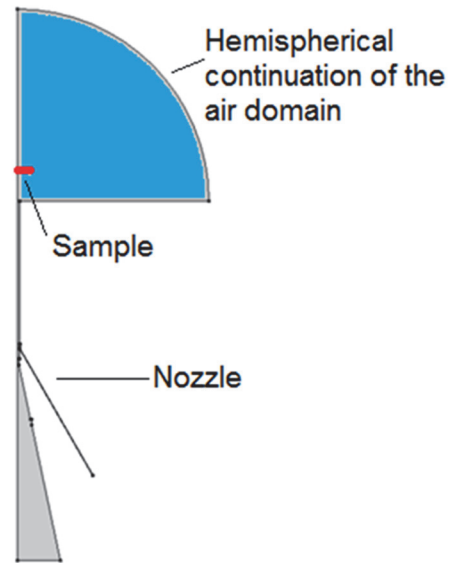


Figure 3: 2D axis-symmetric geometry, including the sample and a hemispherical air domain.

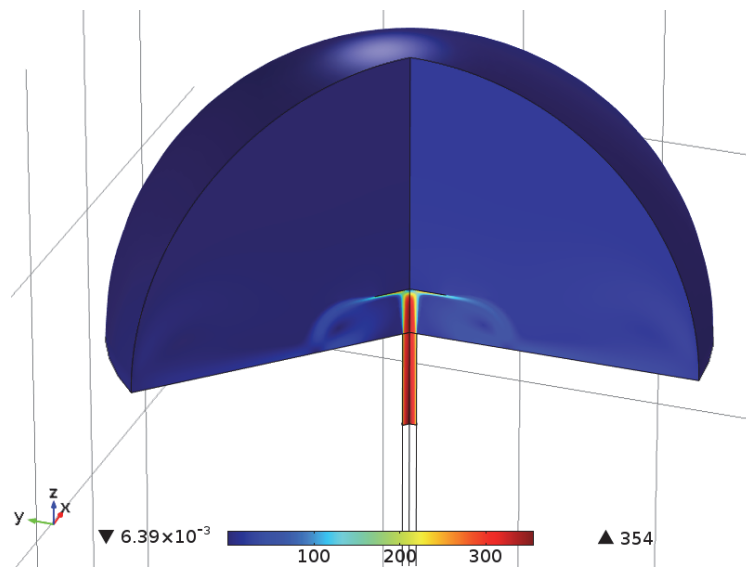


Figure 4: Contour plot of air region plus sample, showing predicted velocities (m/s).

2.2 RSE NOZZLE

The nozzle geometry for this model was provided by RSE (Ricerca sul Sistema Energetico, Italy). The model was set up in COMSOL in the same way as the NPL model, although this model was 2D, rather than 2D axisymmetric, see Figure 5.

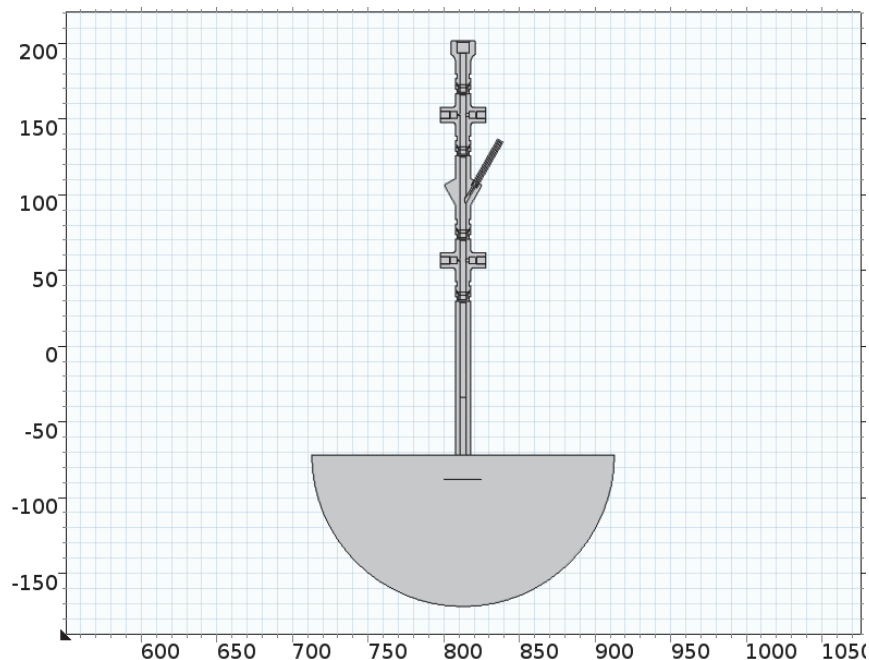


Figure 5: 2D geometry of RSE nozzle, including the sample and a hemispherical air domain.

The initial conditions for the model were a stand-off distance between nozzle tip and sample of 32 mm, an air radius of 100 mm and a sample length of 25 mm. The analysis was run at room temperature and a typical contour plot of velocity magnitude is shown in Figure 6.

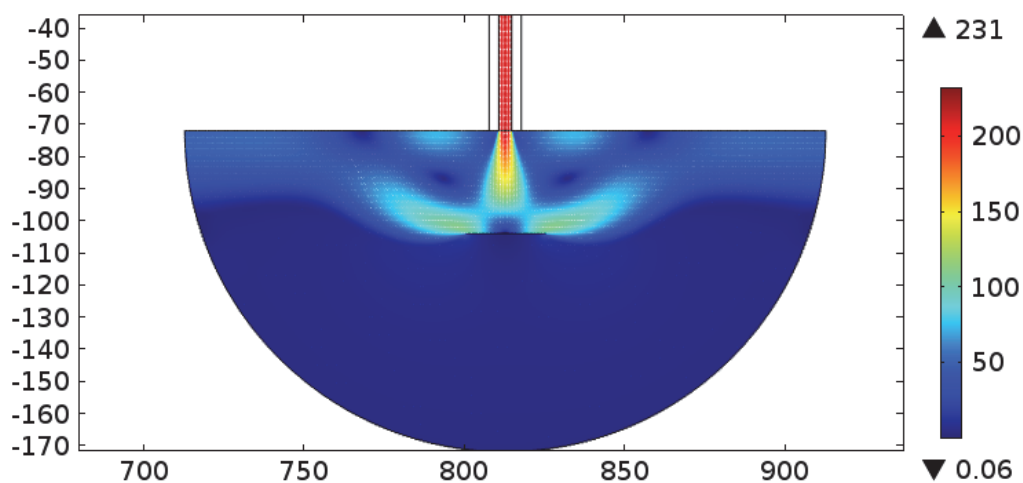


Figure 6: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s).

2.3 SINGLE PARTICLE IMPACT MODEL

The models detailed in sections 2.1 and 2.2 both predict the flow of gas through the nozzle, and into a hemispherical air domain. Particles have not been included in the model, although the particle speed and impact angle are expected to be similar to that of the predicted gas flow [10]. To study the particle/sample interaction an FE model of a single particle impact has been created in Abaqus.

A cubic sample (1 mm^2 , with a depth of 0.5 mm) has been modelled with a defined core region in which impact/damage occurs. This core region has a higher mesh density, see Figure 7. The spherical particle has a diameter of 300 microns, with an impact angle of 45° . The particle has been defined as an analytical rigid surface with movement controlled by a reference node. At the start of the analysis, the particle is very close to the sample surface, moving with a velocity of 100 m/s . Explicit time integration has been used due to the high velocity of the particle. The plastic deformation of the sample is defined by the Johnson-Cook plasticity model. To simulate erosion, element deletion has been included by using the Johnson-Cook damage model. This material model determines whether elements have reached a critical strain level, which then leads to failure of that element. For this example, the particle is steel and the sample is a titanium alloy Ti-6Al-4V.

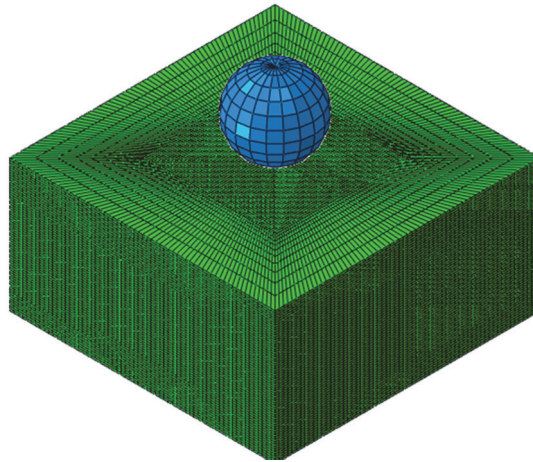


Figure 7: Abaqus mesh of sample plus single particle, with refined mesh in region of contact.

Contact was set-up carefully to ensure that the interior elements of the sample were included in the contact definition, as once element deletion has occurred the interior elements can become the outer surface, see Figure 8. The mass loss due to erosion was output by comparing the total mass of the undeformed sample at the start of the analysis with the total mass of the deformed/eroded sample at the end of the analysis. Analyses have been run with varying parameters such as particle speed and impact angle.

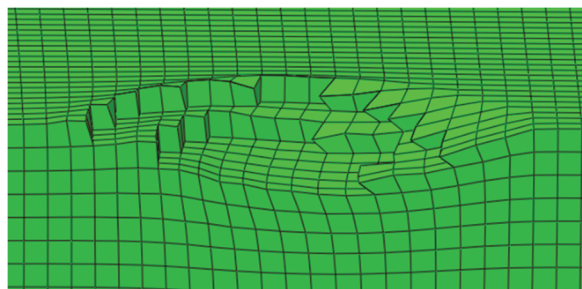


Figure 8: Abaqus deformed mesh showing area of element deletion.

3. PARAMETRIC STUDY DETAILS

Parametric analyses were carried out on the NPL nozzle. The three parameters of interest were temperature, inlet pressure and sample stand-off distance. The baseline model was a temperature of 200 °C, inlet pressure of 1.3 bar and stand-off distance of 16 mm, with each of these parameters being varied individually from this baseline model. The range of parameters used were as follows:

- Temperature: 900 °C to RT in 200 °C increments
- Inlet pressure: 1.3 bar to 1.1 bar in 0.05 bar increments
- Stand-off distance: 16 mm to 48 mm in 8 mm increments

The original plan was to run the parametric study at room temperature but when running the temperature study, it wasn't possible to obtain convergence at temperatures below 200 °C as there were issues with the turbulent flow parameters. So 200 °C was the baseline model temperature used rather than room temperature. At 200 °C the maximum velocity is approximately 250 m/s at the nozzle outlet.

Another point of interest is the effect of impact angle. As the NPL nozzle is a 2D axisymmetric model, this couldn't be varied in this model. Hence the impact angle parametric study was carried out using the RSE 2D model. The parameters studied were:

- Impact angle: 90°, 60°, 45° and 30°

The baseline model for this nozzle was a temperature of 20 °C, flux 12 m³/h and stand-off distance of 32 mm.

4. PARAMETRIC STUDY RESULTS

4.1 EFFECT OF TEMPERATURE

The NPL 'nozzle plus air' model was run with an impact angle of 90°, an inlet pressure of 1.3 bar and a stand-off distance of 16 mm, and temperatures varying between 900 °C and 200 °C. Contour plots of velocity magnitude are shown for temperatures of 900 °C, 700 °C, 500 °C, 300 °C and 200 °C in Figures 9 to 13 respectively. The contour plots are zoomed in to focus on the velocity around the sample.

The horizontal velocity profiles along the length of the sample for all temperatures are plotted in Figure 14. As the model is 2D axisymmetric, only half the sample is modelled, hence a length of zero in Figure 14 represents the centre of the sample.

As can be seen in the contour plots (Figures 9-13) and the velocity profile graph (Figure 14), the velocity is zero at the centre point of the sample. The horizontal velocity increases with distance from the centre point, up to a maximum at approximately 4 mm from the centre. The velocities then decrease slowly before increasing sharply at the edge of the sample. Measurements of erosion scars made at NPL show that the central part of the erosion scar is slightly elevated compared to the ring around it, see Figure 15. The zero gas velocity predicted immediately above the surface of the specimen may explain a slight reduction in erosion at the centre of the scar.

It is also noticeable from the contour plots that the velocity of the gas exiting the nozzle has a high velocity (360 m/s – 254 m/s for temperatures 900 °C to 200 °C). The velocity decreases

markedly before reaching the sample. The presence of the sample itself will be responsible for some of the decrease, at all temperatures studied the velocity of the gas in the region of air just above the sample is still quite high, see Figure 16.

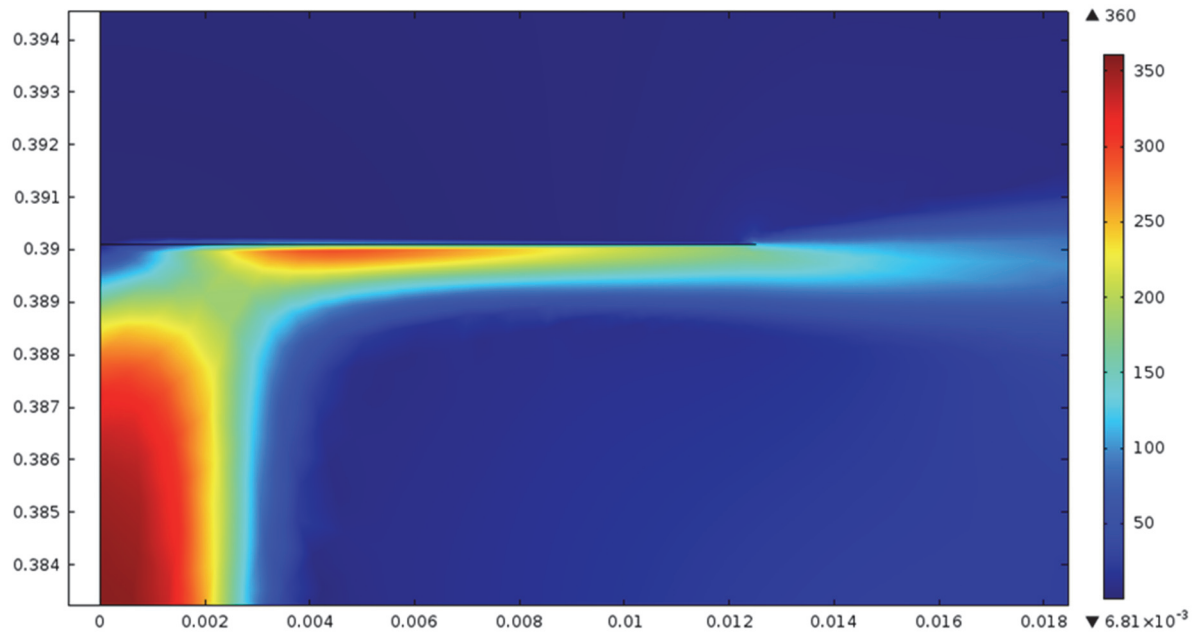


Figure 9: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a temperature of 900 °C.

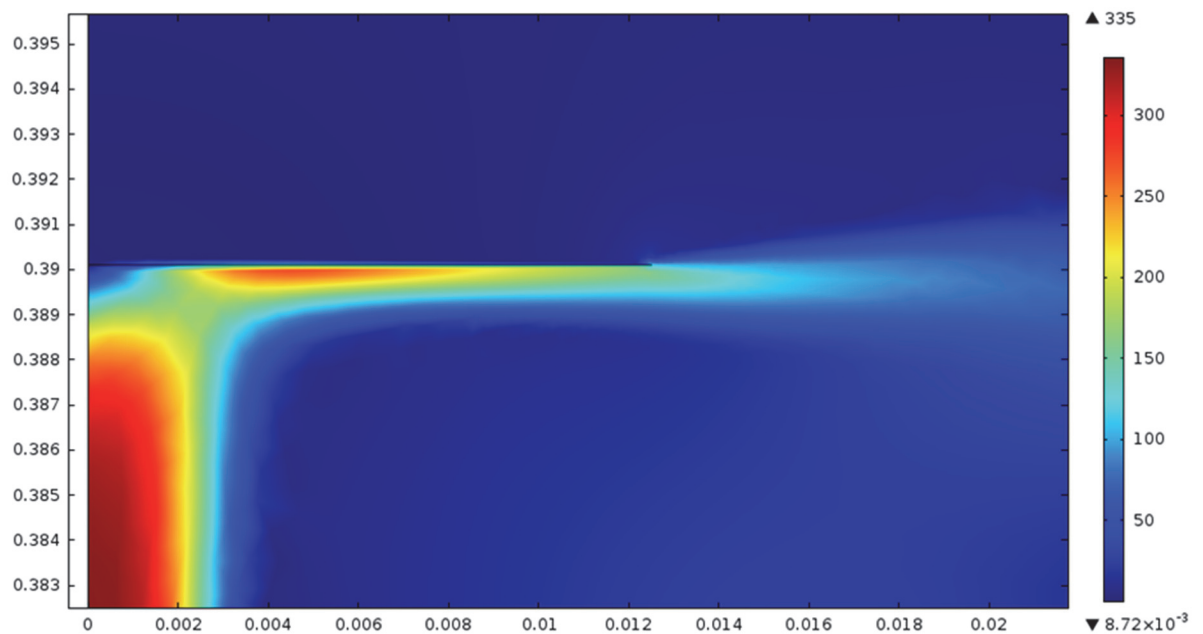


Figure 10: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a temperature of 700 °C.

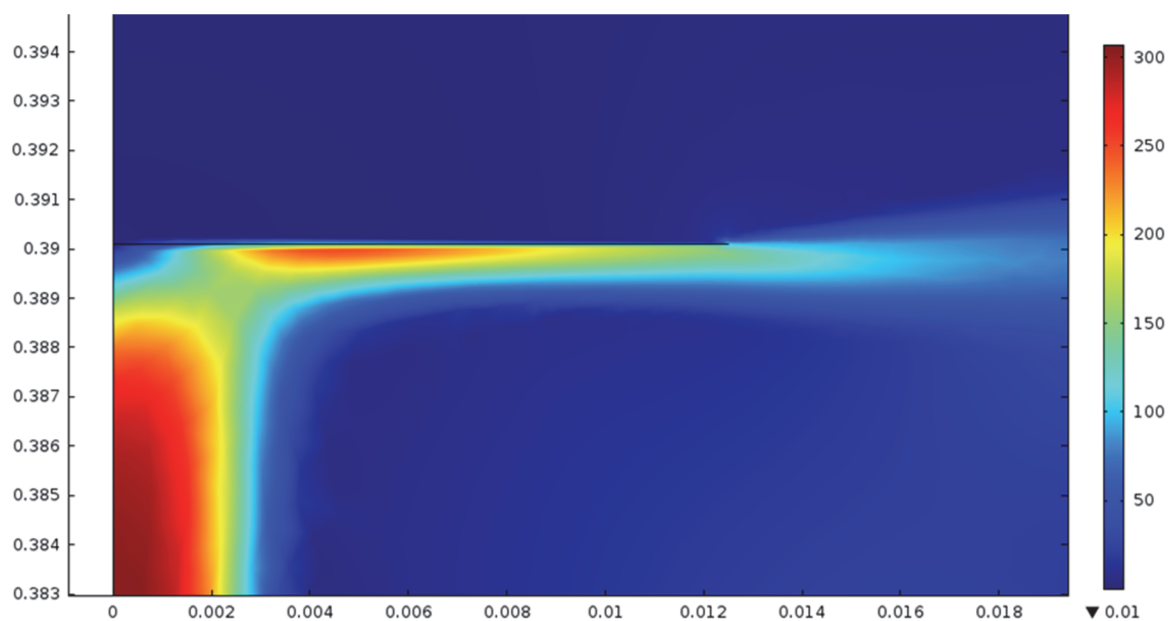


Figure 11: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a temperature of 500 °C.

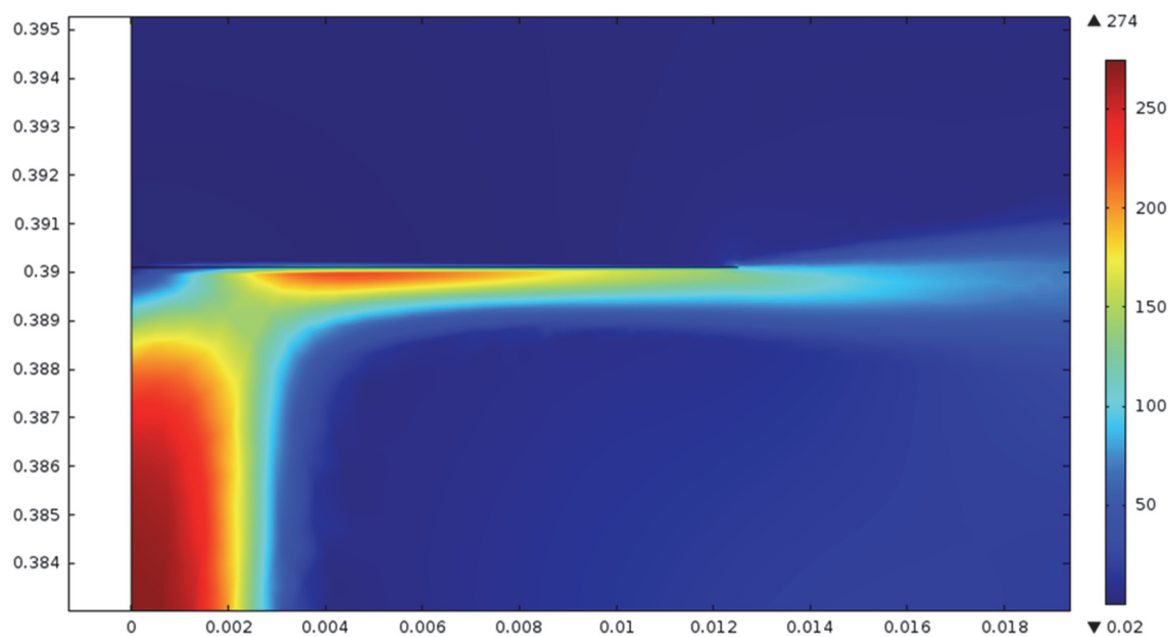


Figure 12: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a temperature of 300 °C.

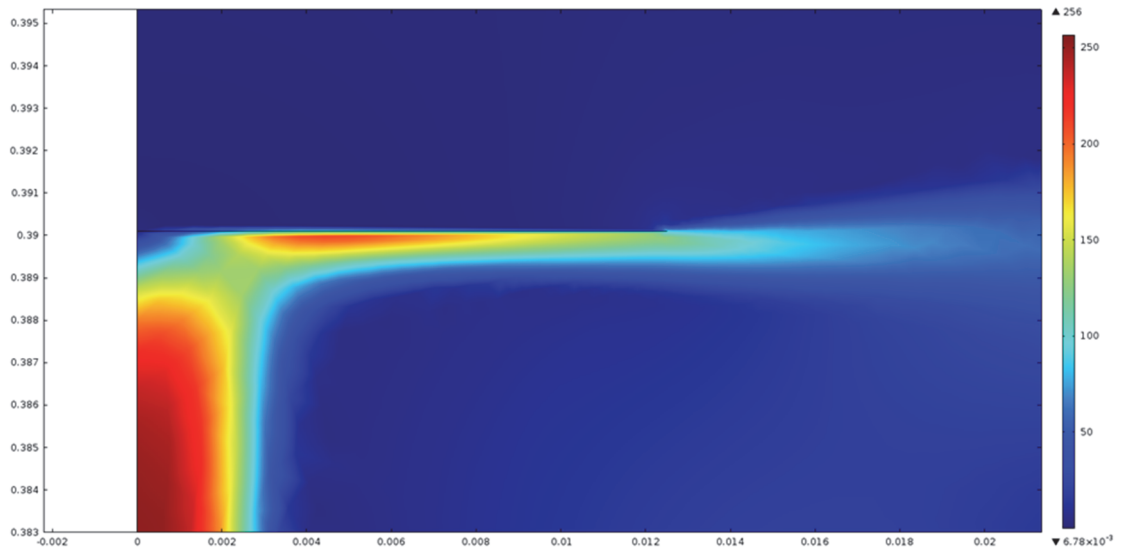


Figure 13: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a temperature of 200 °C.

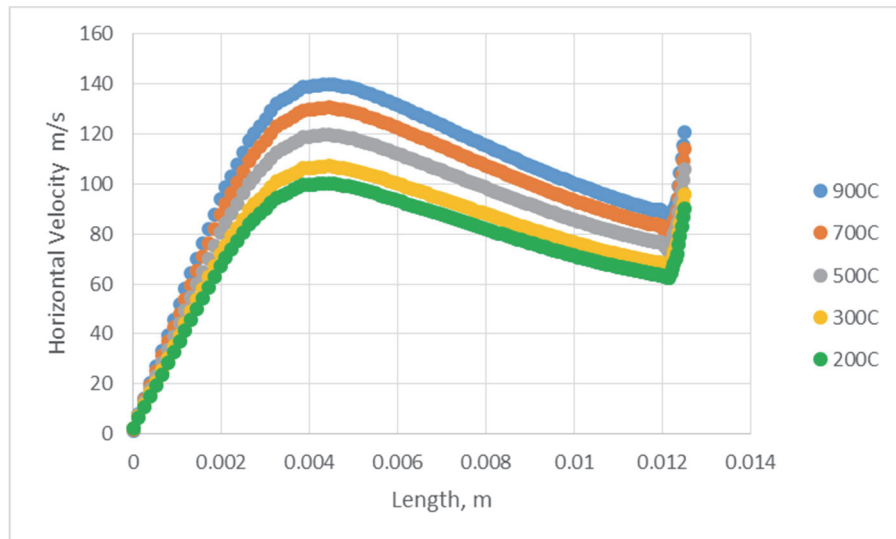


Figure 14: Horizontal velocity profile along the length of half the sample (zero is the centre point of the sample) for the 5 temperatures studied.

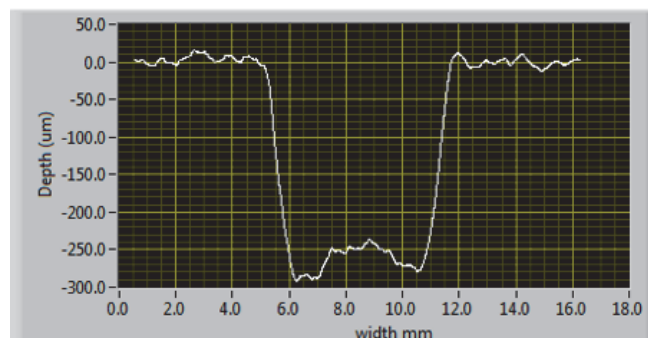


Figure 15: Laser line depth profile measured across an erosion scar.

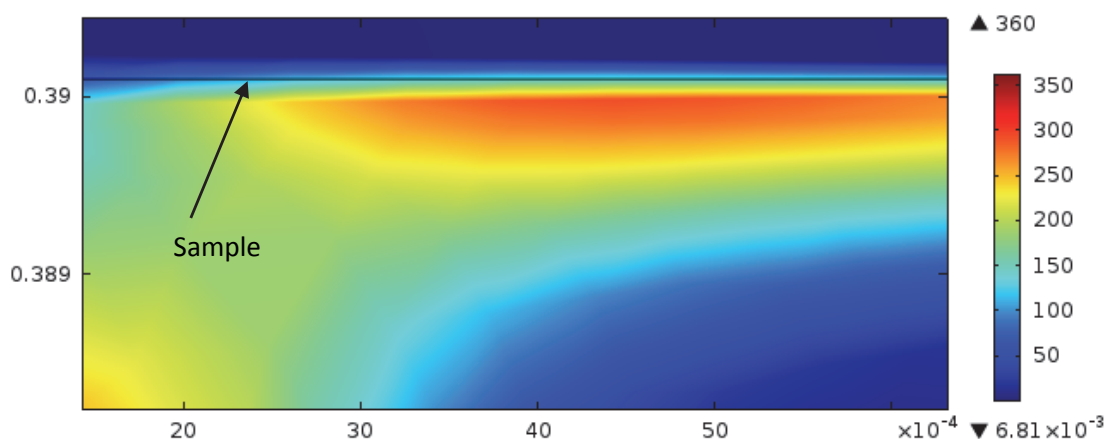


Figure 16: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a temperature of 900 °C in the region close to the sample.

4.2 EFFECT OF INLET PRESSURE

The NPL ‘nozzle plus air’ model was run with an impact angle of 90°, a temperature of 200 °C, a stand-off distance of 16 mm and an inlet pressure varying between 1.3 bar and 1.1 bar in 0.05 bar increments. Contour plots of velocity magnitude are shown for inlet pressure of 1.3 bar, 1.25 bar, 1.2 bar, 1.15 bar and 1.1 bar respectively in Figures 17 to 21. The contour plots are zoomed in to focus on the velocity around the sample.

The horizontal velocity profiles along the length of the sample for all inlet pressures studied are plotted in Figure 22. As the model is 2D axisymmetric, only half the sample is modelled, hence a length of zero in Figure 22 represents the centre of the sample.

It can be seen in Figures 17-22 that as the inlet pressure decreases, the outlet velocity from the nozzle decreases (from 256 m/s to 135 m/s) and the velocity magnitude at the sample surface decreases. The shape of the horizontal velocity profile along the sample is the same as in Figure 14, with zero velocity at the centre point of the sample, increasing to a maximum at approximately 4 mm from the centre, then decreasing slowly before increasing sharply at the edge of the sample. Once again the velocity of the gas in the region of air just above the sample is higher than that at the sample surface. The vertical velocity of the gas flow exiting the nozzle decreases at a faster rate for higher inlet pressures as the gas approaches the sample surface, see Figure 23.

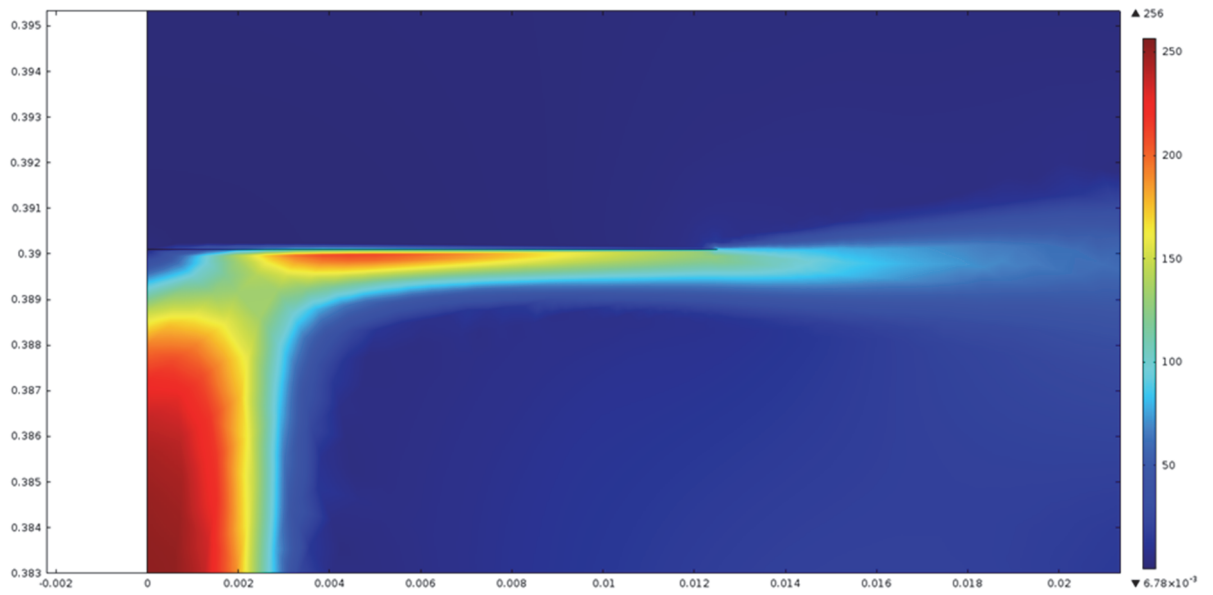


Figure 17: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at an inlet pressure of 1.3 bar.

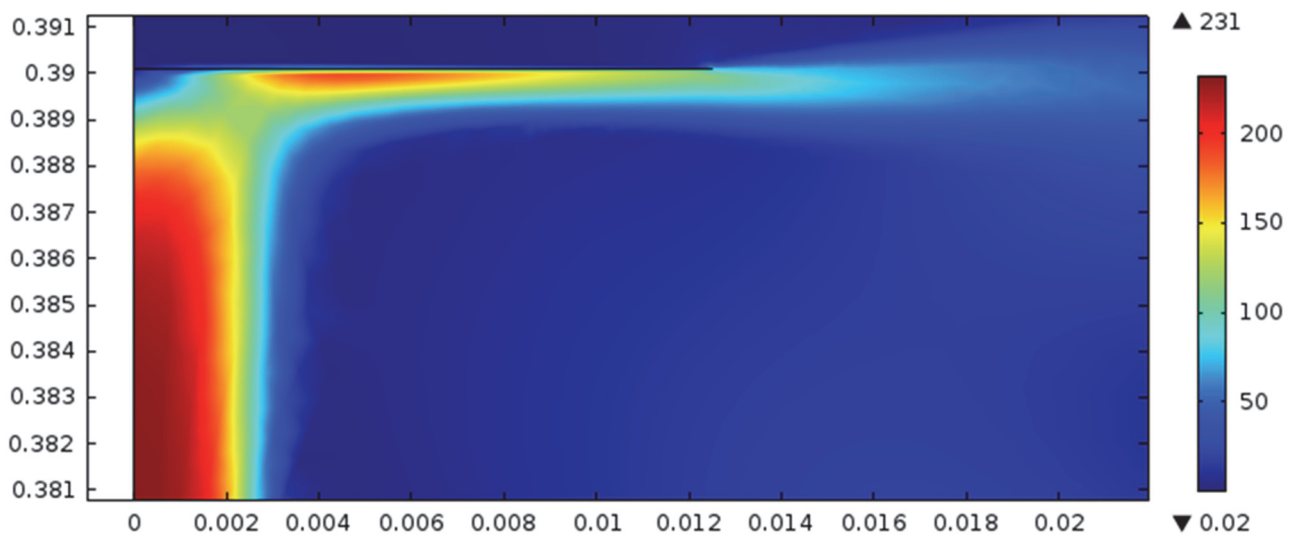


Figure 18: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at an inlet pressure of 1.25 bar.

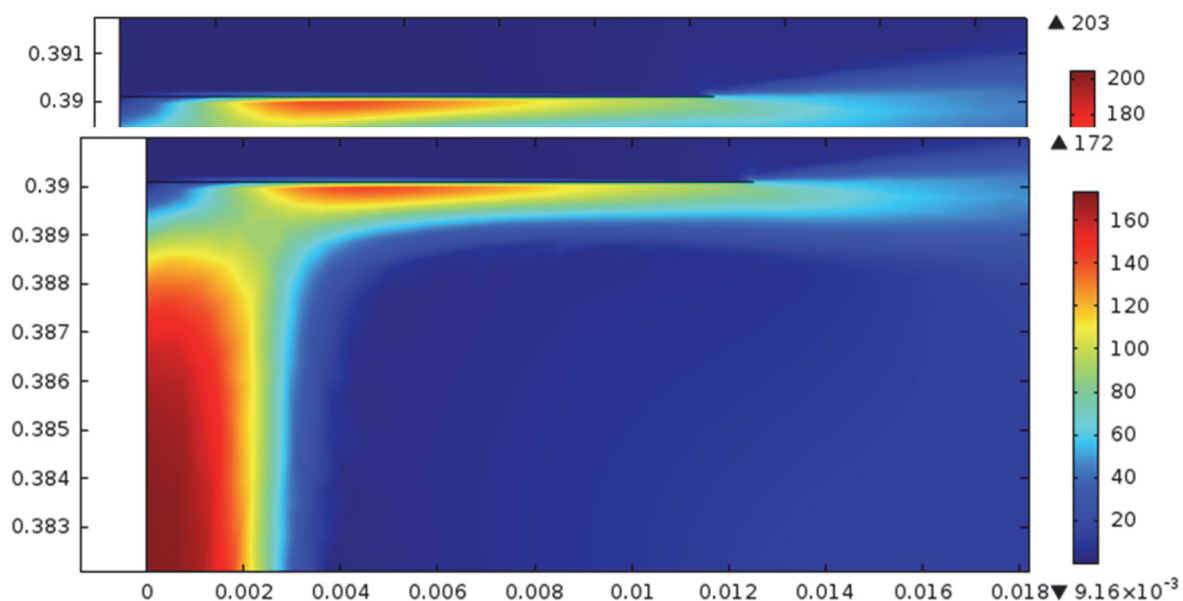


Figure 19: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at an inlet pressure of 1.2 bar.

Figure 20: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at an inlet pressure of 1.15 bar.

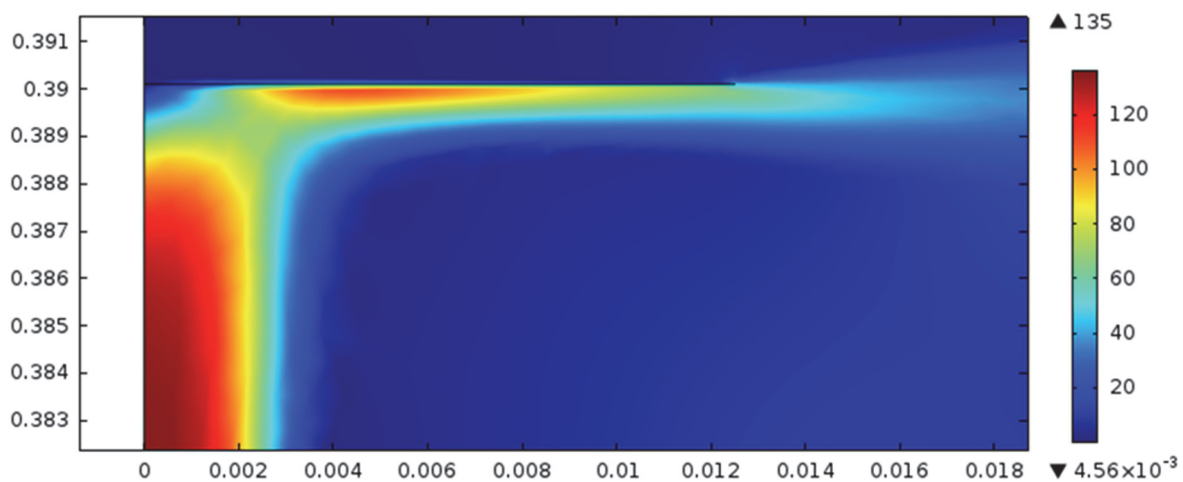


Figure 21: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at an inlet pressure of 1.1 bar.

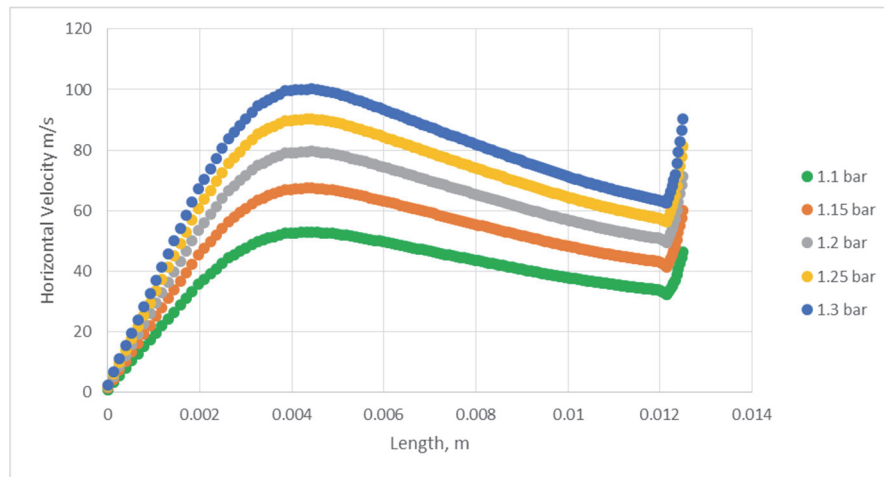


Figure 22: Horizontal velocity profile along the length of half the sample (zero is the centre point of the sample) for the 5 inlet pressures studied.

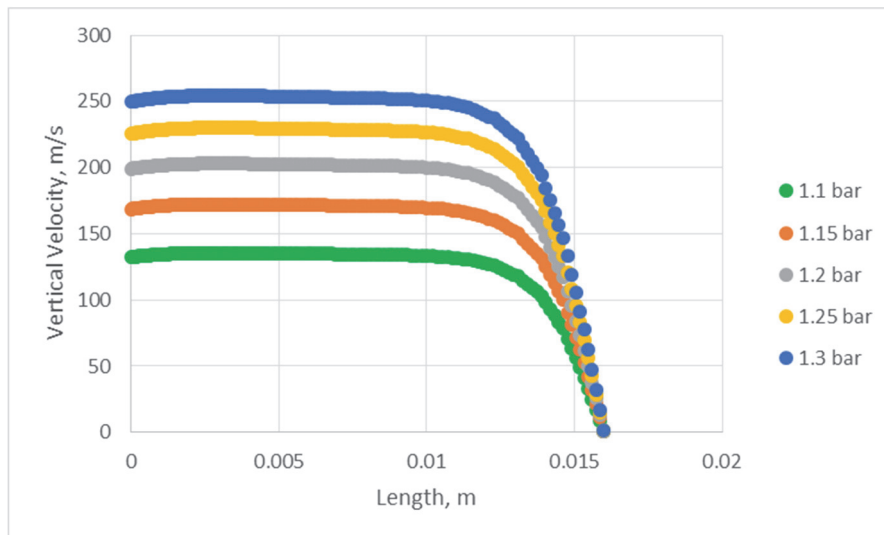


Figure 23: Vertical velocity profile along the centreline between nozzle exit and the sample for the 5 inlet pressures studied.

4.3 EFFECT OF STAND-OFF DISTANCE

The NPL ‘nozzle plus air’ model was run with an impact angle of 90°, a temperature of 200 °C, and an inlet pressure of 1.3 bar. The stand-off distance, i.e. distance between the end of the nozzle and the sample surface, was varied from 16 mm to 48 mm. When the stand-off distance was set to 40 mm, the model failed to converge, hence an alternative stand-off distance of 39 mm was used.

Contour plots of velocity magnitude are shown for stand-off distances of 16 mm, 24 mm, 32 mm, 39 mm and 48 mm in Figures 24 to 28 respectively. The contour plots are zoomed in to focus on the velocity around the sample. The horizontal velocity profiles along the length of the sample for all stand-off distances studied are plotted in Figure 29.

As the stand-off distance has no effect on the gas flow through the nozzle, the maximum velocity shown in the contour plots is constant (260 m/s). At larger stand-off distances, the velocity of the gas reaching the sample is lower and hence the horizontal velocity along the sample is also lower. At smaller stand-off distances, the horizontal velocity along the sample surface is higher. There is only a slight difference in velocity profile for stand-off distances of 16 mm and 24 mm. Once again the velocity of the gas in the region of air just above the sample is higher than that at the sample surface, but the magnitude is smaller for larger stand-off distances.

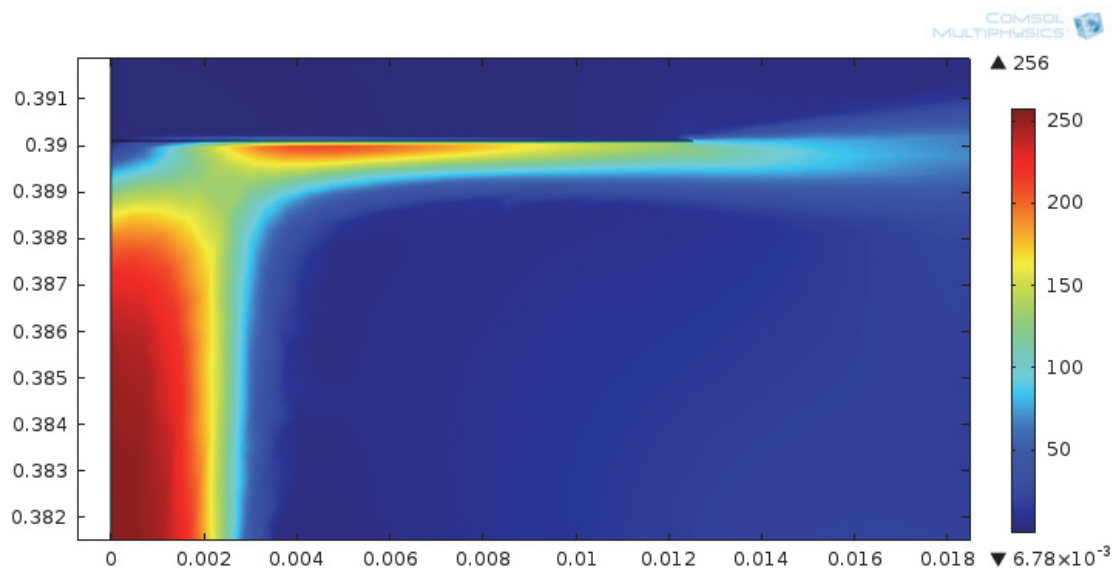


Figure 24: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 16 mm.

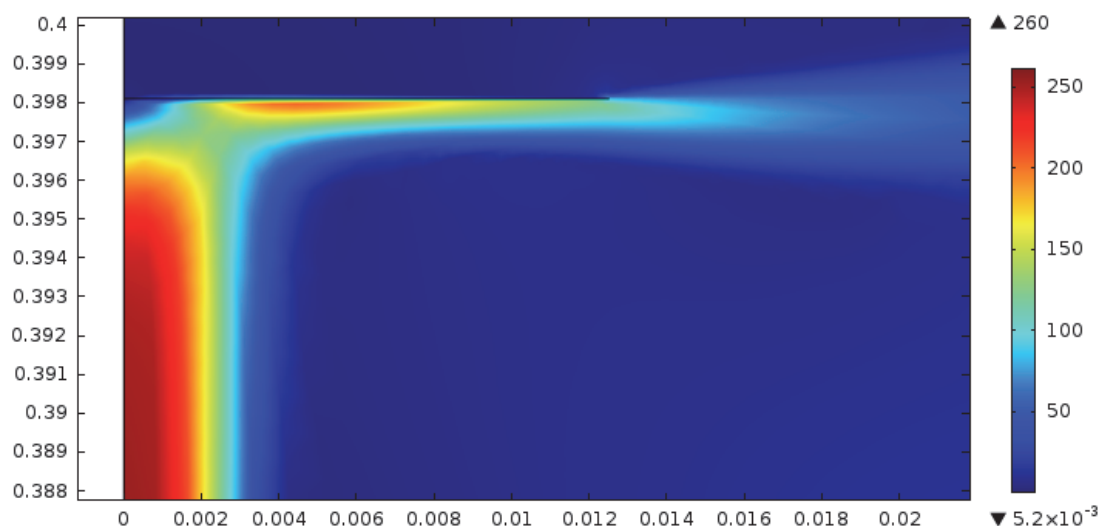


Figure 25: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 24 mm.

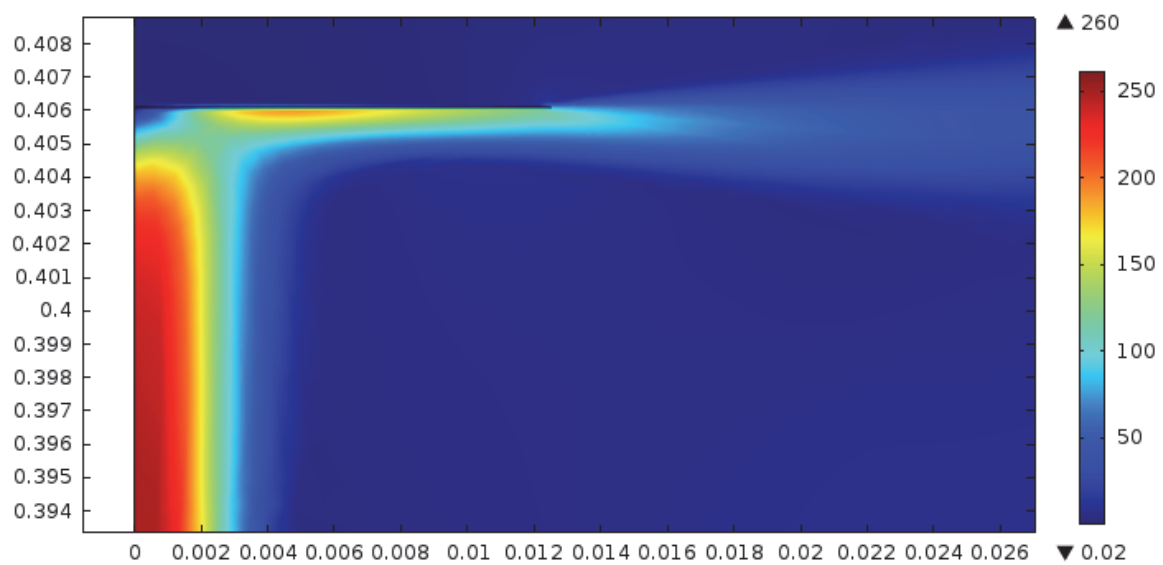


Figure 26: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 30 mm.

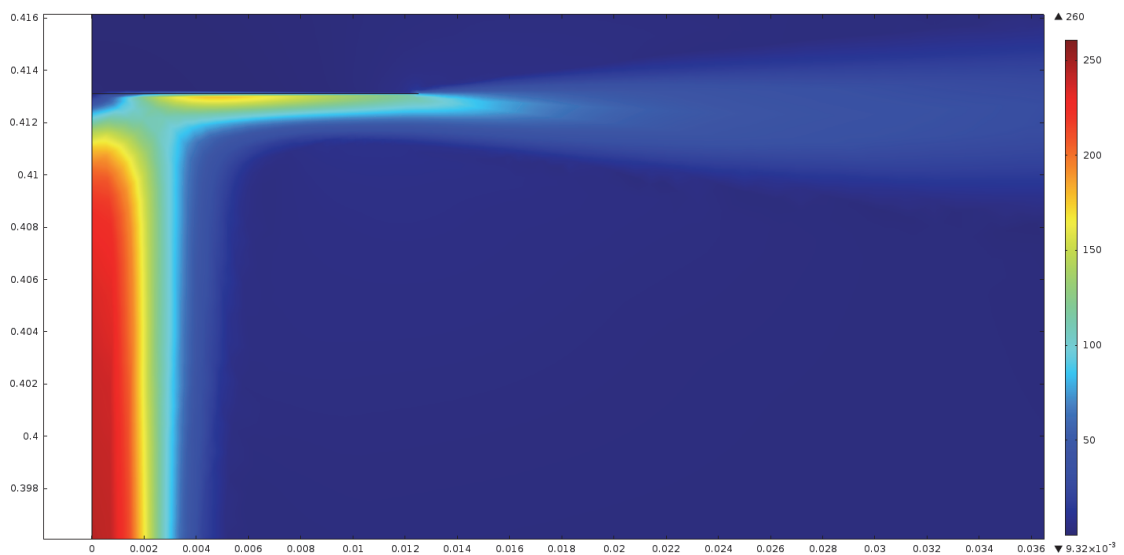


Figure 27: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 39 mm.

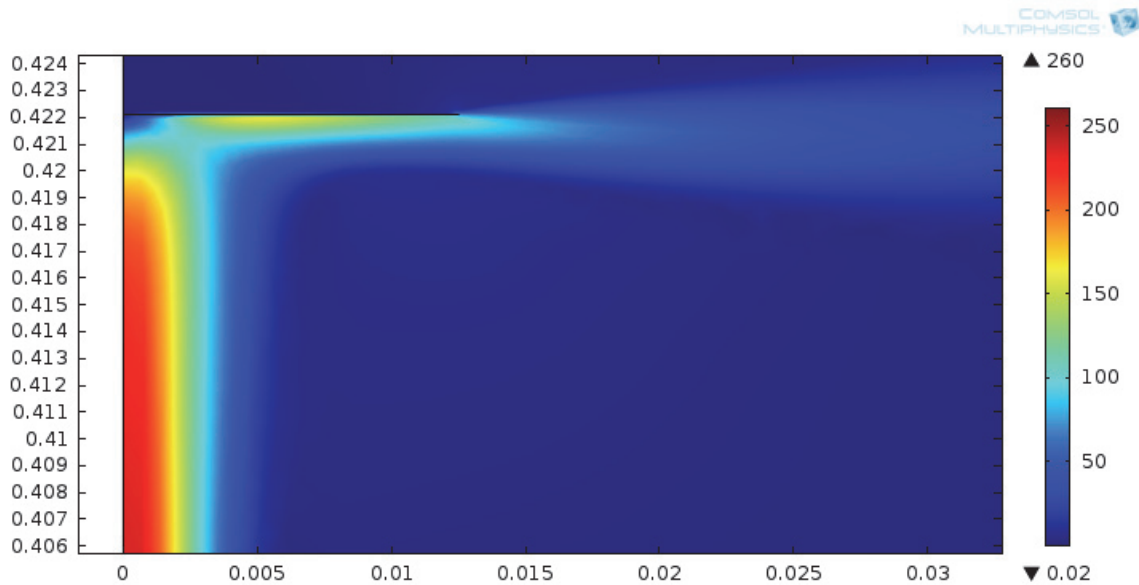


Figure 28: Contour plot of NPL nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 48 mm.

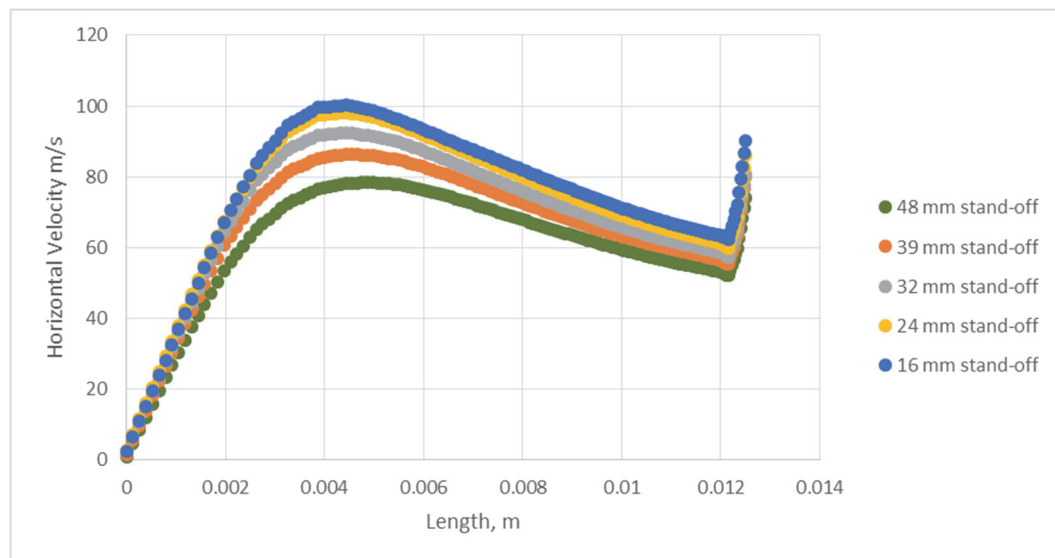


Figure 29: Horizontal velocity profile along the length of half the sample (zero is the centre point of the sample) for the 5 stand-off distances studied.

With the RSE nozzle, an initial model was run at room temperature with an inlet flow rate of 6 m³/h giving an outlet speed of 116 m/s, and a stand-off distance of 16 mm. The velocity contour plot is shown in Figure 30. When the stand-off distance is increased to 32 mm, the inlet flow rate needed to be increased to 12 m³/h to obtain a similar horizontal velocity profile, Figures 31 and 32. In Figure 30, the gas flows upwards sharply at the ends of the sample, with the gas hitting the upper bounds of the air domain. This sudden increase in velocity is also evident in the horizontal velocity plot, Figure 32. At the larger stand-off distance and higher outlet speed (231 m/s) the horizontal velocity is similar to that of the initial model, although interestingly the velocity profile is much smoother, Figure 32, and the gas flow is more diffuse above the sample, Figure 31. The gas flow pattern observed in the RSE nozzle model contour plot, Figure 30, wasn't as obvious in the 2D axisymmetric model of the NPL nozzle, see Figure 24, but the shape of the

velocity profile curve for this model, Figure 32 is similar to that seen in the NPL model. The velocity profile obtained for the 2D RSE model with a stand-off distance of 32 mm and flow rate of 12 m³/h, Figure 32, is much more linear than that predicted from the 2D axisymmetric model of the NPL nozzle.

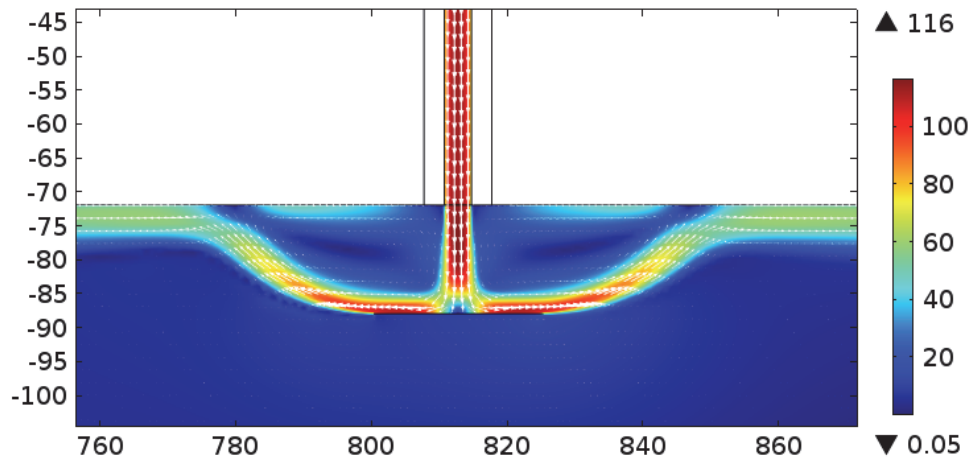


Figure 30: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 16 mm and an inlet flow rate of 6 m³/h.

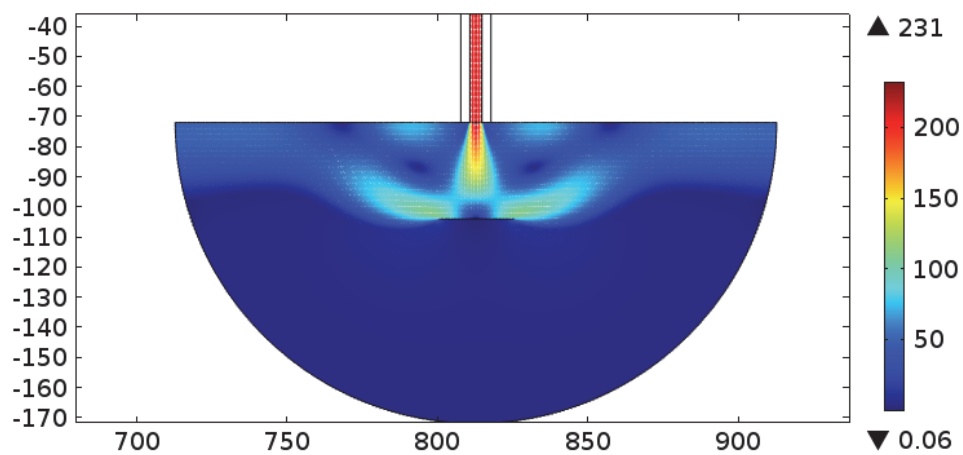


Figure 31: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s) at a stand-off distance of 32 mm and an inlet flow rate of 12m³/h.

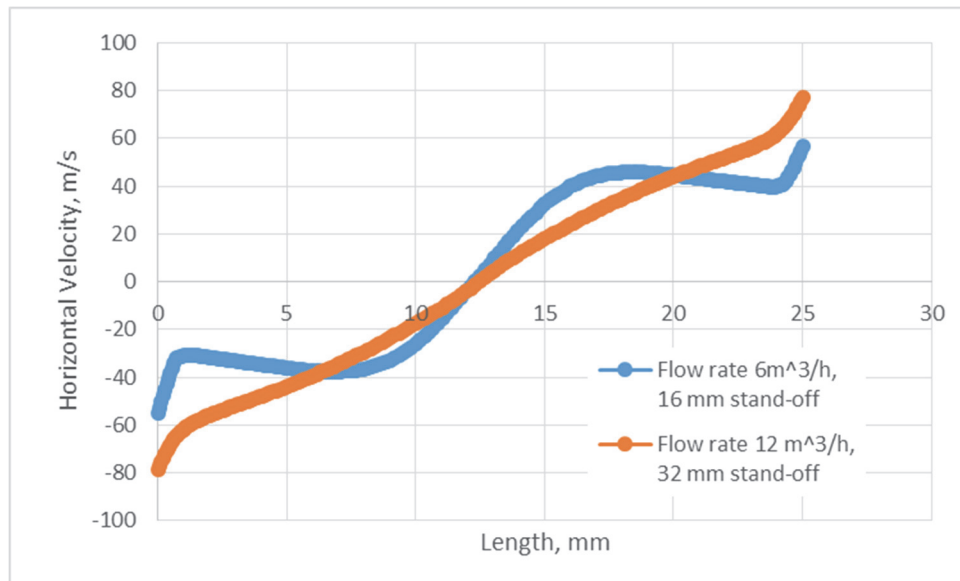


Figure 32: Horizontal velocity profile along the length of the sample for stand-off distances of 16 mm (6 m³/h flow rate) and 32 mm (12 m³/h flow rate).

4.4 EFFECT OF IMPACT ANGLE

The impact angle of gas/particles is an important parameter in determining the degree of erosion in an erosion test. The NPL nozzle is 2D axisymmetric which means that it is not possible to use this model to investigate the effect of gas flow impact angle. If the angle of the sample was changed, it would result in a conical sample.

Instead the 2D RSE model has been used. The sample has been rotated about the centre point to give impact angles of 90°, 60°, 45° and 30° while keeping the stand-off distance to the centre point constant. The analyses were run at room temperature (20 °C) and an inlet flow rate of 12 m³/h and a stand-off distance of 32 mm.

Contour plots of velocity magnitude within the nozzle and air region are shown for impact angles of 90°, 60°, 45° and 30° in Figures 33, 35, 37 and 39 respectively. The horizontal velocity, vertical velocity and velocity magnitude profiles obtained along the length of the sample (i.e. data output along the line representing the sample) for the four angles studied are presented in Figures 34, 36, 38 and 40 respectively.

In all cases, the initial velocity on nozzle exit was 231 m/s, with velocity decreasing as the gas spreads out in the air region. At an impact angle of 90° (Figures 33 and 34) there is an area with zero velocity at the centre point of the sample with a steep gradient in horizontal velocity (and velocity magnitude) either side. The vertical velocity is zero along the length of the sample. At a 60° impact angle (Figures 35 and 36), both horizontal and vertical velocity components exist, with the horizontal velocity being the largest. At 45° impact angle (Figures 37 and 38) the horizontal and vertical velocity components are equivalent, while in the case of a 30° impact angle (Figures 39 and 40) the vertical component of velocity is the largest.

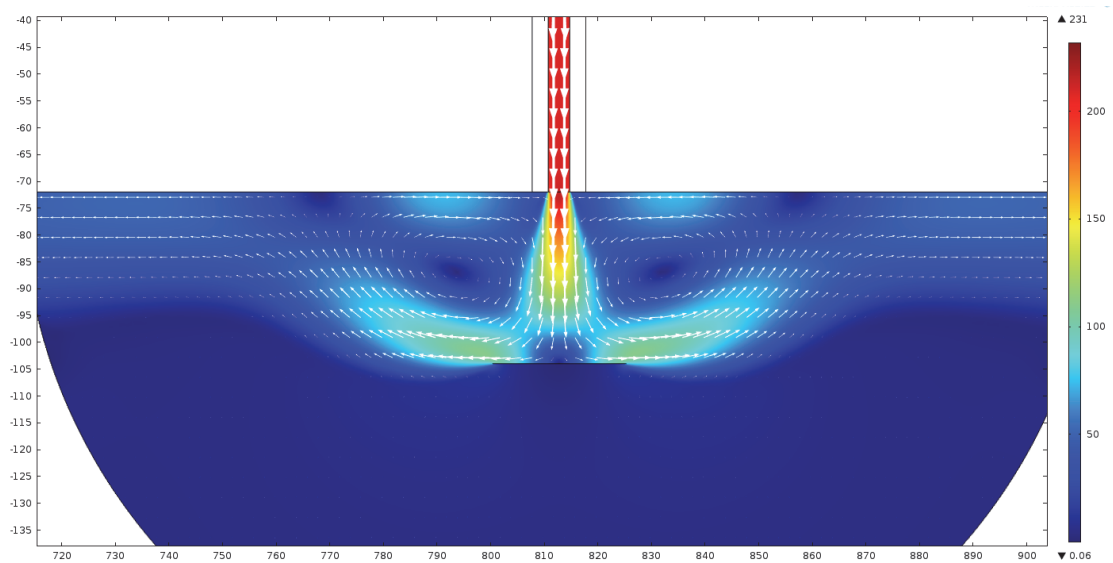


Figure 33: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s) at an impact angle of 90° .

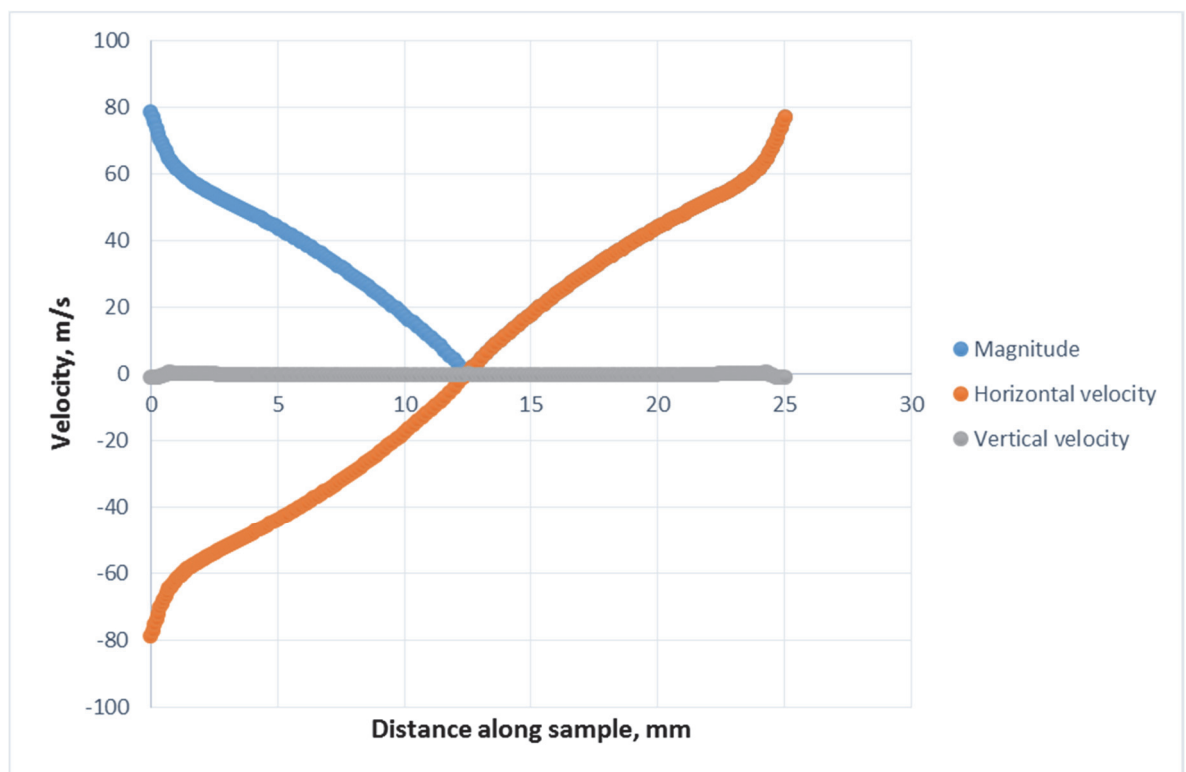


Figure 34: Velocity profiles (horizontal, vertical and magnitude) along the length of the sample for an impact angle of 90° .

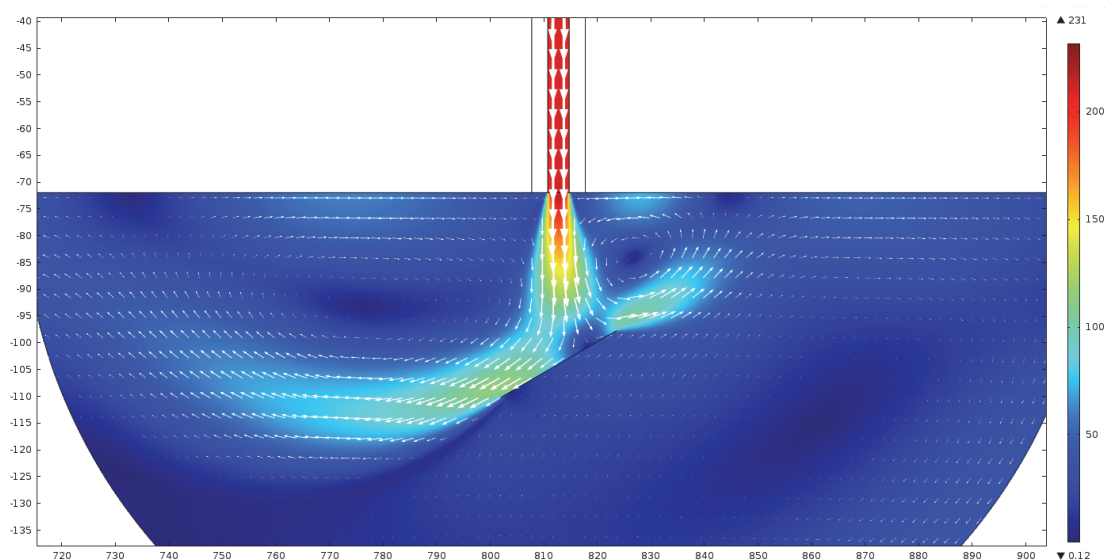


Figure 35: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s) at an impact angle of 60° .

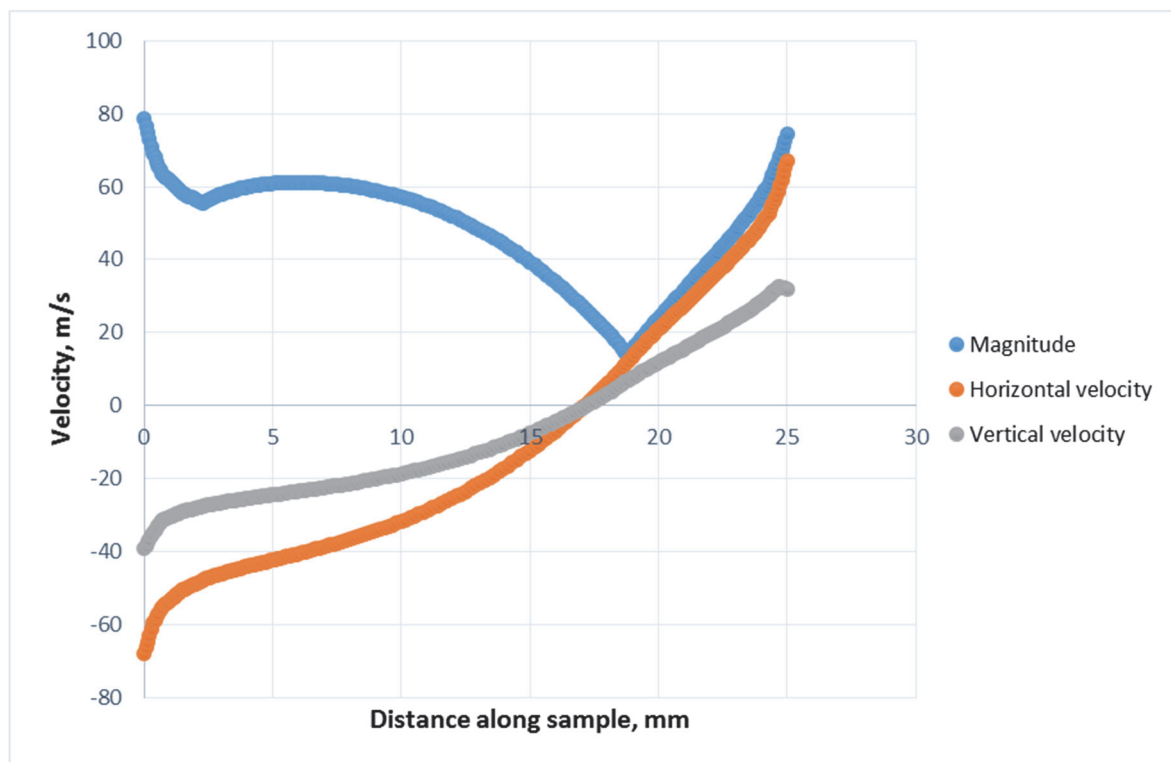


Figure 36: Velocity profiles (horizontal, vertical and magnitude) along the length of the sample for an impact angle of 60° .

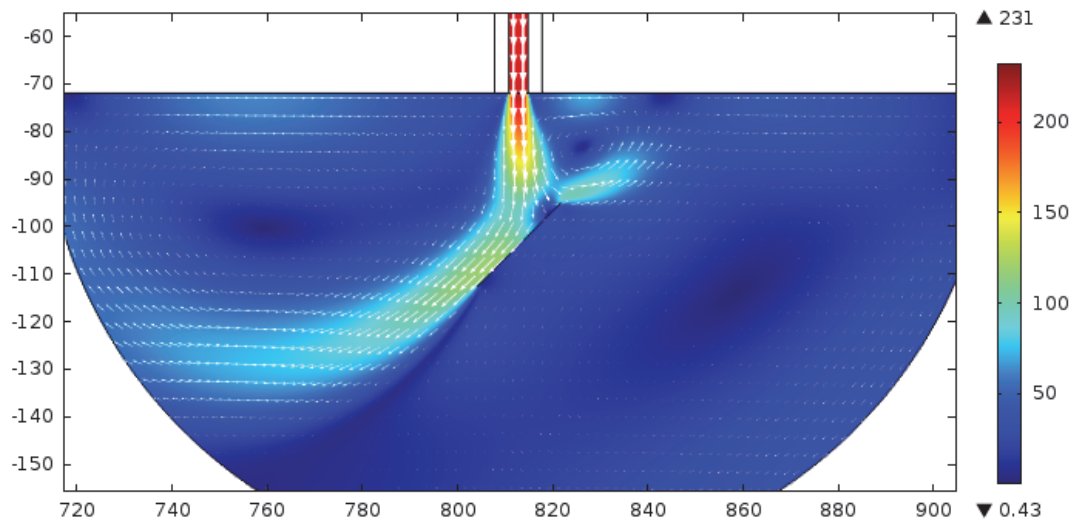


Figure 37: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s) at an impact angle of 45° .

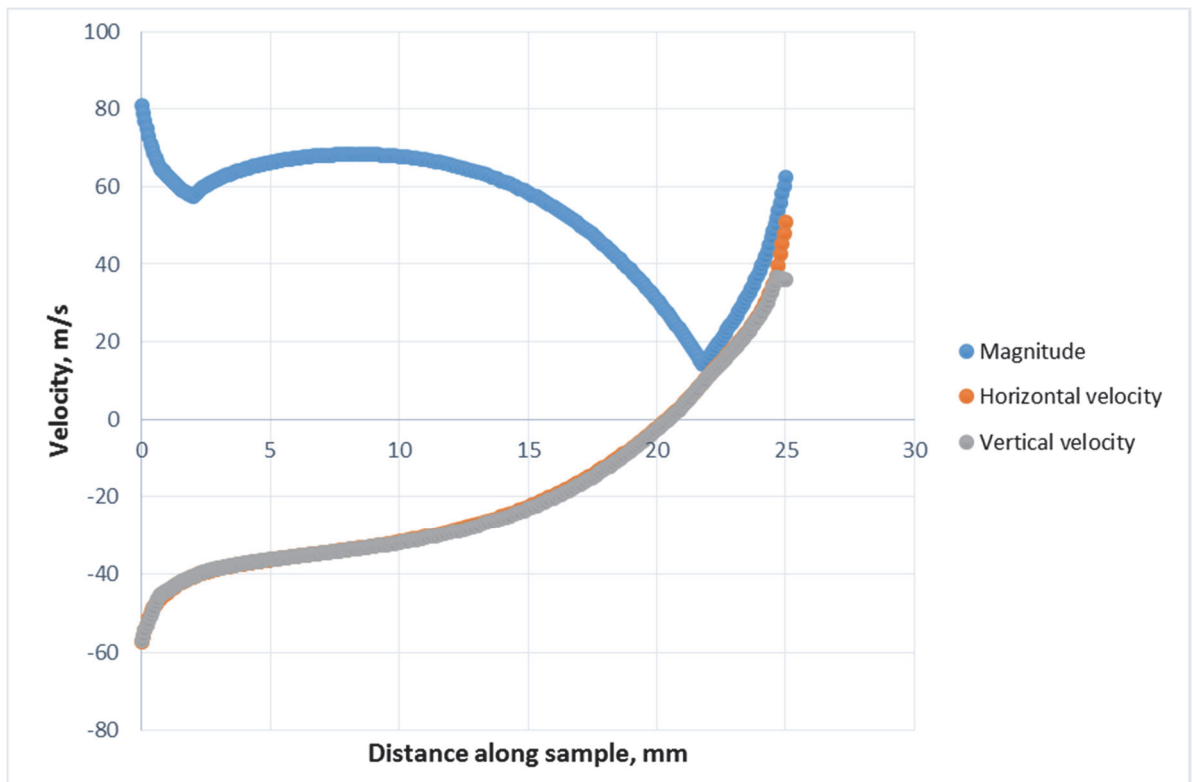


Figure 38: Velocity profiles (horizontal, vertical and magnitude) along the length of the sample for an impact angle of 45° .

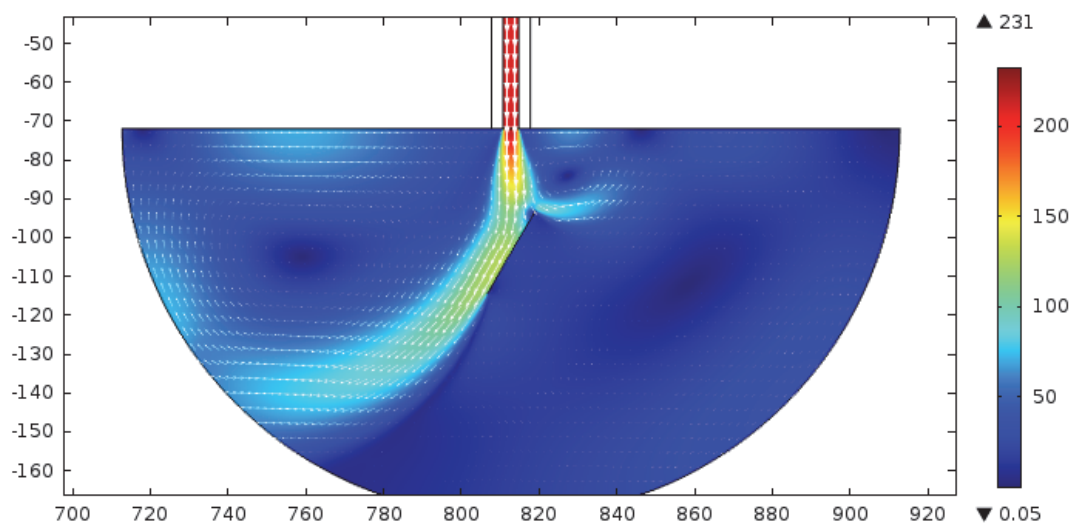


Figure 39: Contour plot of RSE nozzle, air region plus sample, showing predicted velocities (m/s) at an impact angle of 30°.

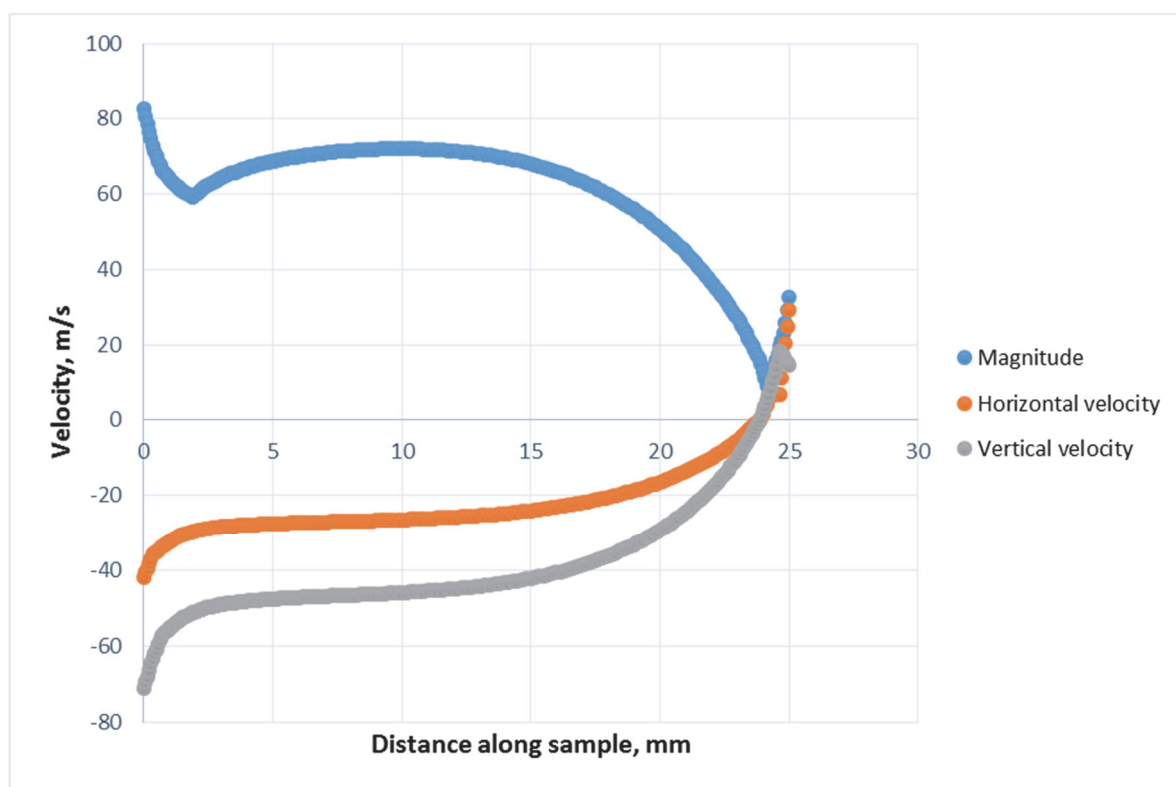


Figure 40: Velocity profiles (horizontal, vertical and magnitude) along the length of the sample for an impact angle of 30°.

As the impact angle becomes smaller, the horizontal velocity profile becomes smoother, see Figure 41. At all angles there are locations on the surface that have zero horizontal and vertical velocities, but these locations are slightly off-set so that, apart from at an impact 90°, the velocity magnitude does not fall to zero along the sample surface, see Figure 42. From Figure 41 the best conditions for erosion testing would appear to be glancing angle e.g. 30°, as a large area of stable velocity is achieved at this angle.

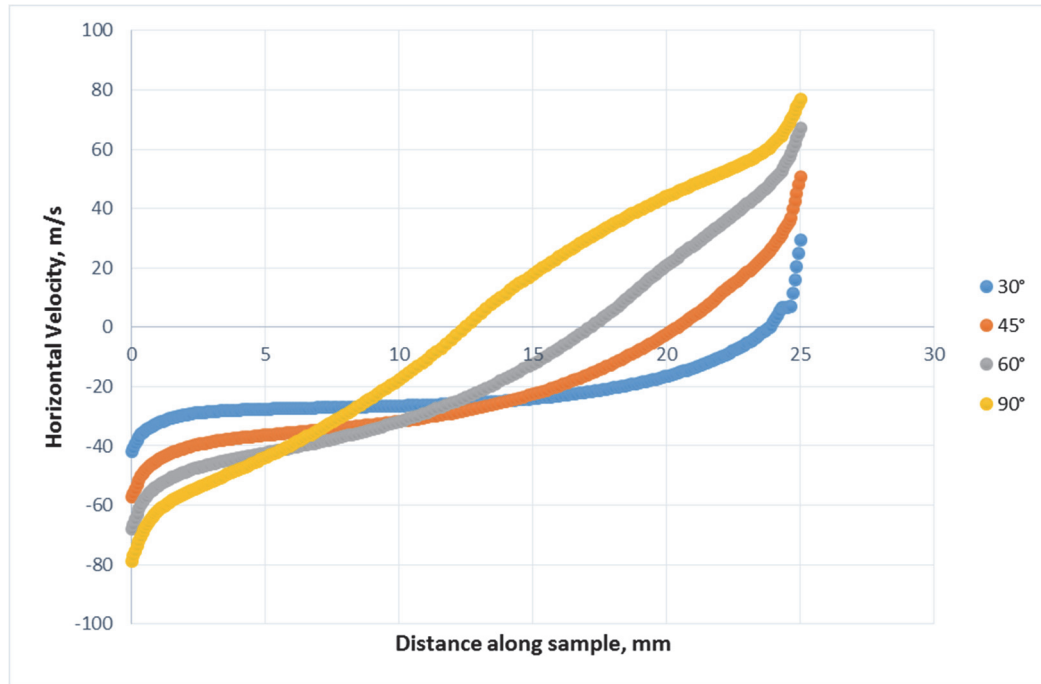


Figure 41: Horizontal velocity profile along the length of the sample for impact angles of 90°, 60°, 45° and 30°.

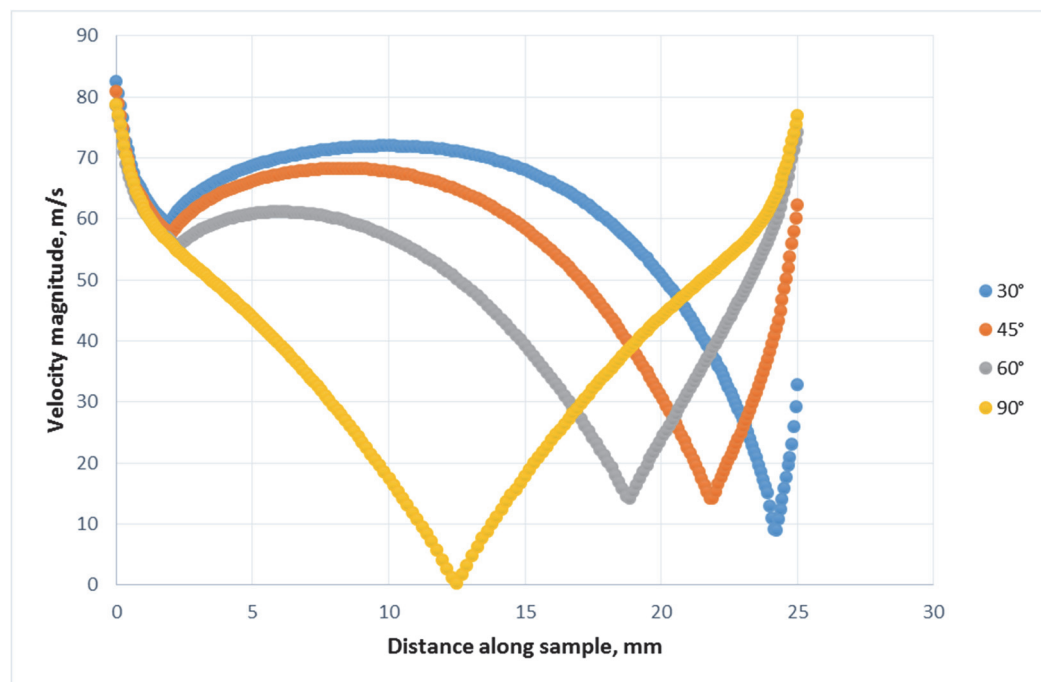


Figure 42: Velocity Magnitude profile along the length of the sample for impact angles of 90°, 60°, 45° and 30°.

The effect of particle impact angle has been studied using the single particle FE model. The model has been run with the particle impacting the surface at 90°, 60°, 45° and 30° at an impact speed of 100 m/s.

The velocity magnitude of the particle for each of these analyses is plotted in Figure 43. At a 90° impact angle, the velocity drops to zero during impact as the particle bounces off the surface with no erosion occurring. As the impact angle decreases, the drop in velocity lessens until at 30° the velocity profile is much smoother. In all curves, the flat velocity region is the velocity of the particle after losing contact with the surface. The horizontal velocity of the particle is zero at 90° as expected and highest at 30°, see Figure 44.

There is also a noticeable change in the vertical displacement of the particle with impact angle, Figure 45. At higher impact angles such as 90° and 60°, the inward and outward displacement of the particle is quite symmetric (where the particle bounces). At lower angles, the displacement profile shows the particle skims across the surface causing more erosion, see Figure 46. From this graph it is clear that a 45° impact angle gives the highest erosion rate.

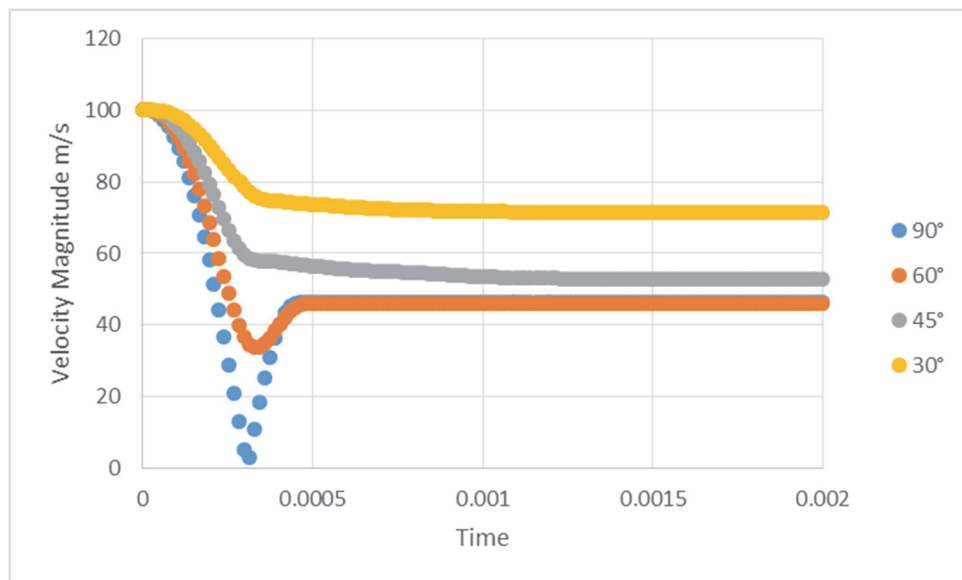


Figure 43: Velocity magnitude profile of the particle from the FE single impact analyses for impact angles of 90°, 60°, 45° and 30°.

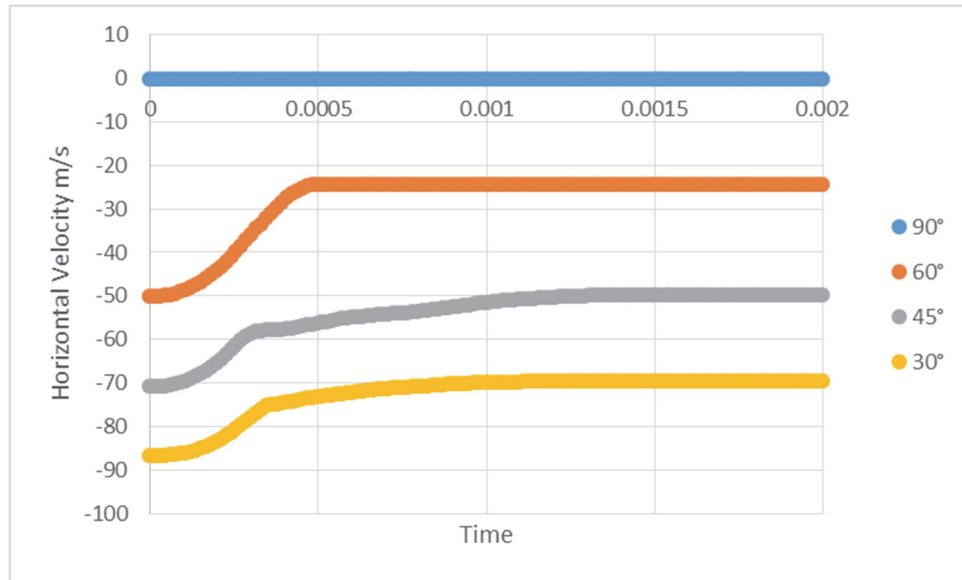


Figure 44: Horizontal velocity profile of the particle from the FE single impact analyses for impact angles of 90°, 60°, 45° and 30°.

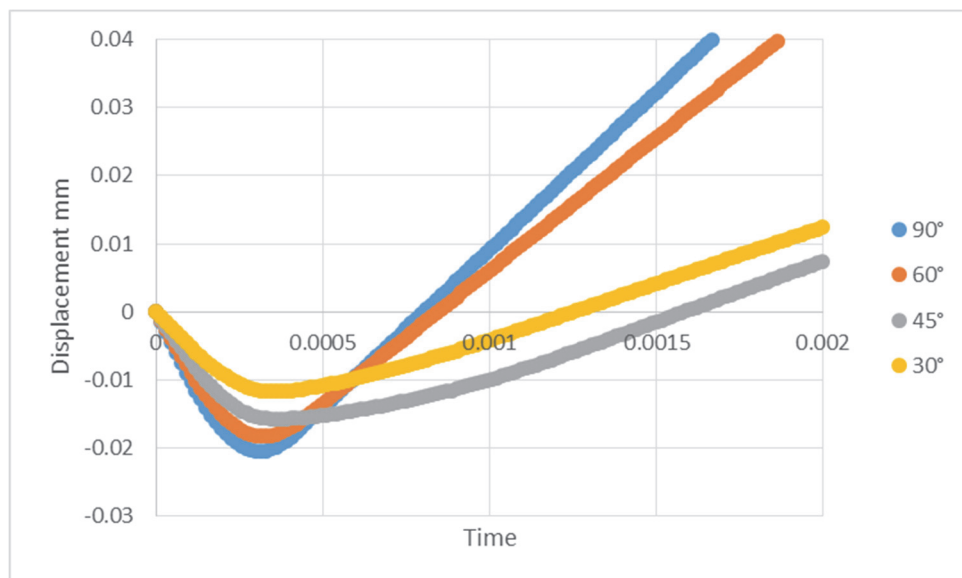


Figure 45: Vertical displacement profile of the particle from the FE single impact analyses for impact angles of 90°, 60°, 45° and 30°.

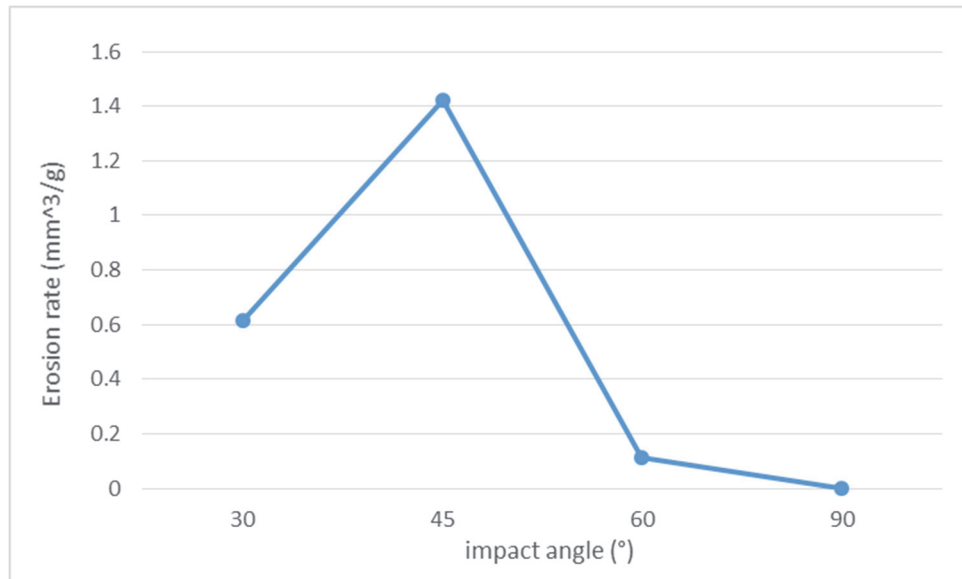


Figure 46: Predicted erosion rates from the FE single impact analyses for impact angles of 30°, 45°, 60° and 90°.

Because the FE single particle impact model is capable of predicting erosion, the link between the horizontal velocity component and erosion can be investigated. Predictions have been obtained from a particle impacting the surface at 45° at speeds of 150 m/s, 100 m/s and 50 m/s which give horizontal velocities at impact of approximately 100 m/s, 70 m/s and 35 m/s which are similar to the horizontal velocities predicted in the NPL nozzle, Figure 22.

The predicted erosion rate is plotted against horizontal velocity in Figure 47, and from this graph it looks like there is a clear correlation between horizontal velocity and erosion rate. But when data from other impact angles are included, it is no longer so clear cut, see Figure 48. In this graph, an increase of horizontal velocity from 0 to 50 m/s has virtually no effect on the predicted erosion rate. At higher horizontal velocities, erosion is obtained but the rate does not correlate with the horizontal velocity. The horizontal velocity of a particle impacting at 30° and 100 m/s is high (~ 90 m/s) but the predicted erosion rate is lower than the preceding data point. A similar graph is obtained for the vertical velocities, see Figure 49. The first three points of this graph seem to indicate a trend of increased erosion with increasing vertical velocity, but there are two points with high vertical velocities (~ 90 m/s and 100 m/s) where the erosion rate drops significantly. These two data points are for impact angles of 60° and 90°. These graphs emphasise that the erosion rate is not dependent solely on the individual velocity components, but is also strongly dependent on the actual impact angle.

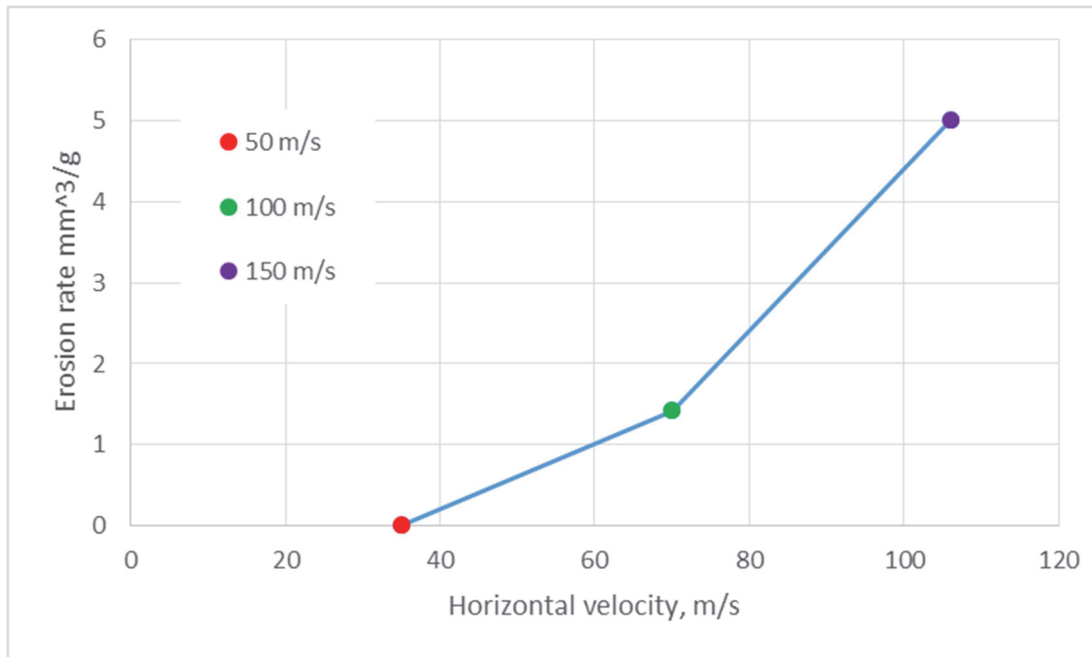


Figure 47: Predicted erosion rates against horizontal velocity, obtained from the FE single impact analysis with an impact angle of 45° and initial particle speeds of 50m/s, 100m/s and 150m/s.

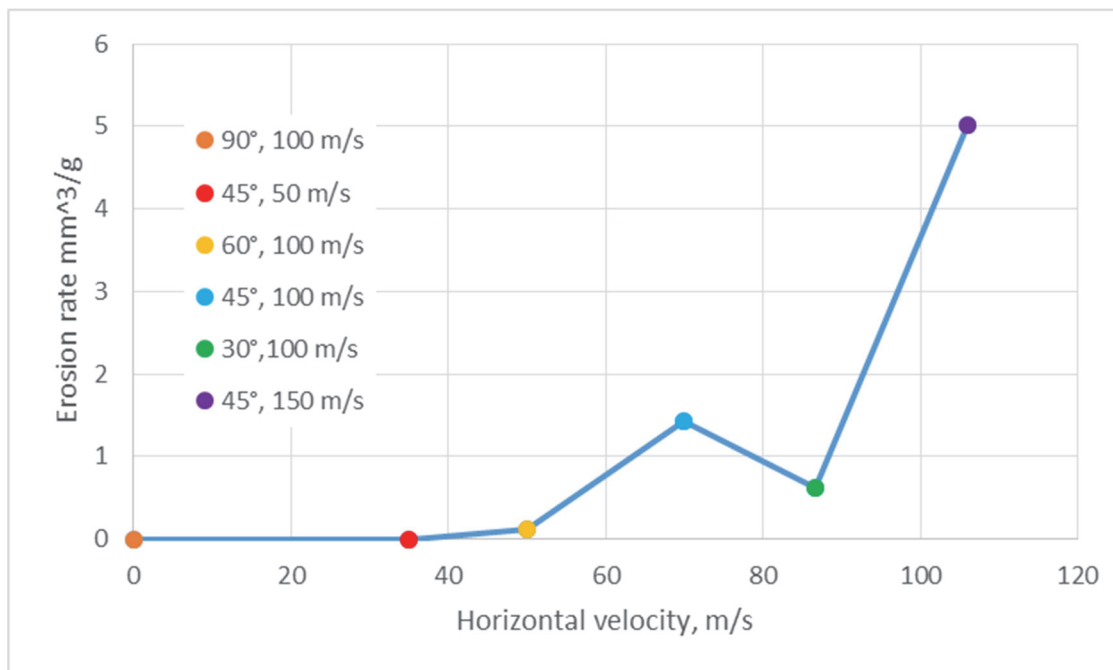


Figure 48: Predicted erosion rates against horizontal velocity, obtained from the FE single impact analyses with impact angles of 30°, 45°, 60° and 90°.

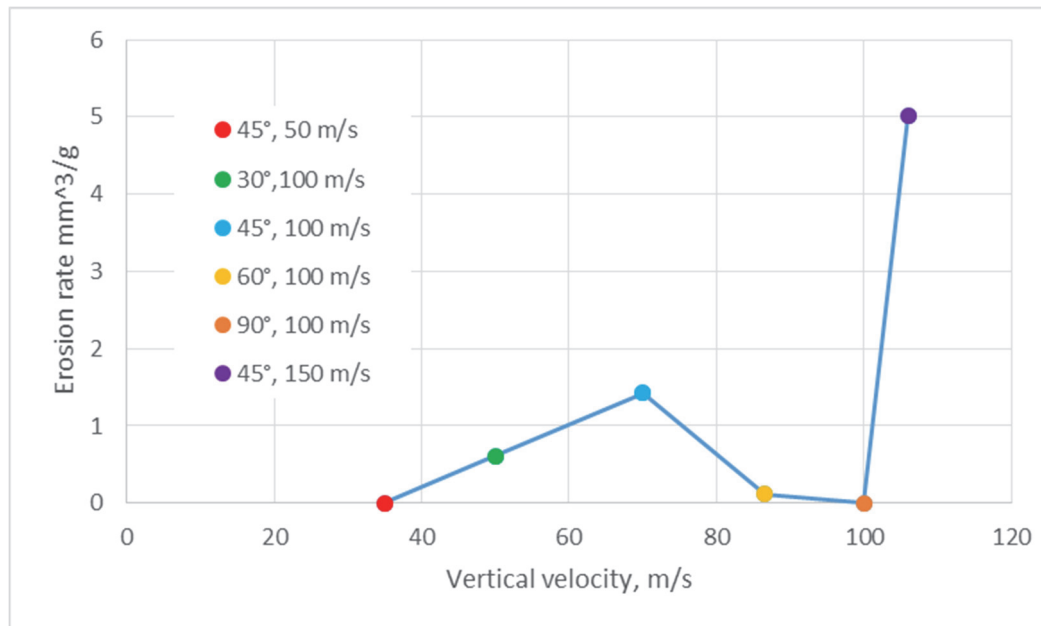


Figure 49: Predicted erosion rates against vertical velocity, obtained from the FE single impact analyses with impact angles of 30°, 45°, 60° and 90°.

5. CONCLUSIONS

Finite element (FE) models of an erosion nozzle, sample and air domain are described for both the NPL erosion nozzle and the RSE nozzle. These models have been used to predict the gas flow through the nozzle, and the gas plume as it leaves the nozzle and reaches the sample. A brief overview of a single particle impact FE model used to predict erosion has also been presented.

The nozzle models have both been used in parametric studies to investigate the effect of parameters such as temperature, inlet pressure, stand-off distance and impact angle on the gas flow exiting the nozzle and the velocities of the gas along the length of the sample. As the nozzle models do not include particles, the FE single particle model has been used to give information regarding particle behaviour near the sample surface and to predict erosion rates at different impact angles.

The studies have shown that in all models, the gas velocity (particle velocity in the single particle model) decreases markedly before contact with the sample surface. There is a region just above the sample surface where gas flow is predicted to be higher.

At lower temperatures and inlet pressures, the gas velocity is lower both on nozzle exit and along the sample. At smaller stand-off distances, the velocity of the gas is higher when it reaches the sample. At larger stand-off distances, the outlet velocity needs to be increased to obtain a similar velocity profile along the sample surface.

The impact angle of gas/particles is an important parameter in determining the degree of erosion in an erosion test. Predictions from the RSE nozzle show that the velocity profile along the sample changes significantly with angle. When considering the horizontal component of velocity, glancing angle impact, i.e. 30°, looks to give the best conditions for erosion testing as a large area of stable velocity is achieved. The single particle FE model also predicts that a 30°

impact angle gives the smoothest velocity profile. This model shows clear trends in the prediction of erosion rate with varying impact angle along with changes in the particle behaviour, from bouncing of the surface to skimming along the surface causing more erosion and possible particle embedding. Investigations into the effect of the individual velocity components suggest that the magnitude of the horizontal component of velocity cannot be used as a direct measure of likely erosion rate, but that the impact angle also needs to be considered.

6. ACKNOWLEDGEMENTS

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