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Study of flow structure in erosion prone complex geometries

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Abstract. Erosion is a challenge in a wide range of industries where fluid is transferred through pipes, valves and other mechanical arrangements. Wear can occur due to a variety of mechanisms but is often related to the presence of droplets or solid particles in the fluid stream. This article presents a study of flow relevant to solid particle erosion in a converging-diverging axisymmetric geometry. The purpose of the study was firstly to investigate the flow characteristics as a function of changes in geometry and compare with empirical data. Secondly, steady state, transient simulations and geometrical simplifications were compared to investigate methods of reducing computational time. Thirdly, the flow structure from each simulation was compared to identify any discrepancy in the simulated velocities in the near wall areas, where erosion is observed, in the diverging section of the geometry. The accuracy of simplified models compared to experimental data were found to be satisfactory with respect to global parameters such as pressure drop and flow coefficient. However, the comparison of steady state, transient, axisymmetric sectioning and full models identified significant discrepancy in local velocities in erosion prone areas, which would affects any erosion rate prediction significantly.

1. Introduction

In many industries the predication of erosion is a critical factor for safe and cost-efficient operation of equipment as erosive damage can range from manageable wear to component failure. Numerical methods alone can be an adequate means for predicting erosion but it can be challenging to state the accuracy of such methods without specific experimental references. In many cases experimental and “real life” tests indicate that numerical analysis predicts the location of erosion adequately [1], [2],[3]. Yet, erosion rate is often underpredicted in complex geometries [4]. The discrepancy between numerical and experimental erosion rates can be challenging with respect to component lifetime prediction. Numerical erosion prediction are in many cases based on simulation of velocity field, introducing particles, calculating particle trajectories and further applying a model for the particle wall interaction [5]. The following work will focus on the fluid flow structure and velocity profiles from the velocity field.

The work presented is based on a study where the purpose is to investigate variation in flow structure due to change in parameters such as geometry. The geometrical parameters in question for this study is the opening, needle position relative to seat and vena contracta, as presented in Figure 1. Further, numerical simulations and experimental data have been used to investigate change in pressure and flow coefficient. Numerical simulations alone have been used to investigate and compare variations in velocity profiles. Relevant parameters from the simulations have been compared with experimental erosion data for the given geometry.

The general aim of the study is to obtain data that can assist in determining areas contributing to the discrepancy between numerical and experimental erosion prediction.

As the study is indented for industrial application all simulations are based on widely used CFD codes, numerical models and turbulence models. It is greatly beneficial to simplify simulations in order to reduce computational time, especially when investigating a wide range of flow parameters and erosion parametrically. This has been the incentive for investigating and comparing discrepancies between numerical simulations.

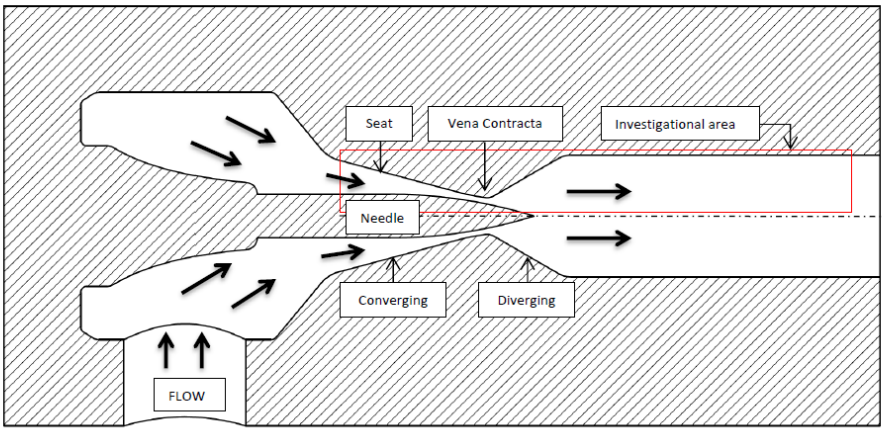

Figure 1. Overview of the geometry used in this study.

2. Erosion theory and method

Solid particle erosion is a phenomenon that is widely studied and many theories and models have been developed in order to describe the removal of material as particle impinge on a surface [4]. The variety of erosion models are many and display a range of strengths and weaknesses for a series of applications. A widely used model in numerical erosion prediction is the erosion model as presented and used in DNV RP 0501 [6] and in Haugen's work [7]. The equation shown below displays the general fundamental model and the most relevant parameters contributing to the erosion.

$$\dot{E} \sim \dot{m}_p \cdot K \cdot U_p{}^n \cdot F(\alpha) \quad (1)$$

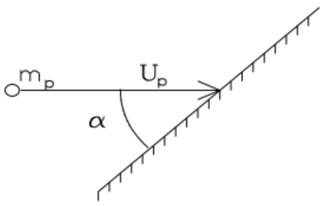

Figure 2. Particle velocity, angle and mass overview [6].

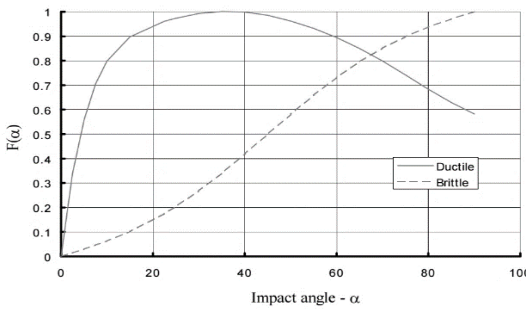

Figure 3. Typical material function F(α) as a function of particle impact angle for ductile and brittle materials.

The material function as presented in Figure 3 is typically determined experimentally for individual cases and is a function of the particle impact angle, as shown in Figure 2. Note that the erosion rate is exponentially related to the velocity of the particle at impact. The exponent n, is found to be in the range 1.4 to 4.6 dependent on surface material [8]. It becomes apparent that any error in particle velocity, which is a calculated based on velocity field, results in a potentially large error in the wear prediction.

3. Flow coefficient

Pressure differential between inlet and outlet, fluid temperature, density and mass flow are considered to be global parameters. These parameter are important with respect to the geometry characteristics, performance, and furthermore the design and appropriate dimensioning of equipment. The performance of the geometry is usually presented by a flow coefficient curve (CV Curve) which is obtained by measuring the flow and pressure drop at a series of constrictions. For the relevant geometry the change in needle position relative to seat is the primary method of controlling the restriction of fluid. The relationship between pressure drop and flow rate achieved by the restriction is commonly referred to as the flow coefficient, CV [9], and is represented by equation (2) for incompressible flow.

$$CV = \frac{Q}{N}\sqrt{\frac{\rho_1/\rho_2}{\Delta P}} \tag{2}$$

Which is reduced to its simplest form as presented in equation (3).

$$CV = Q\sqrt{\frac{SG}{\Delta P}} \tag{3}$$

The CV information enables operators to calculate the relationship between flow rate and pressure drop for a given geometrical restriction and can be used with other equation sets in ISA75.01 [9] to predict flow characteristics of other fluids and conditions. Flow coefficient information is a powerful tool, and is considered to be the governing information used for equipment dimensioning in industry. Hence, the importance of accurate prediction of flow coefficient becomes apparent especially with respect to designing geometries for specific flow conditions.

The following work presents a comparison between a laboratory test and simulated CV values. The overall aim is to identify how well the available tools and simulation simplifications predict the global parameters, such as pressure and flow rate, relative to the experimental data.

Experiments were performed on the specific geometry as seen in Figure 1, at National Engineering Laboratory, NEL, Scotland. The test were completed according to Control valve test procedure ISA 75.01 [10]. Measurements were conducted with a complete valve as an industrial test used for verification of geometry sizing tools. CFD simulations were performed on an identical geometry (converging-diverging section) with analysis details as presented in Table 1. The test comprised of 33 test points across 10 restrictions. All points, flow rates and respective pressures where simulated and compared with the experimental data from NEL. The results and test set up is presented in Figure 4 and Figure 5, respectively.

Table 1. Sectioned geometry, steady state analysis parameter overview.

Parameters	Description
Software	ANSYS CFX 16.2
Analysis Type	Steady State, single phase
Turbulence model	SST
Geometry Description	2 ID upstream, 6 ID downstream vena contracta. 5 degree, axisymmetric section
Fluid	Water, constant properties
Boundary conditions	Inlet:Mass, Flow Outlet: Average Static Pressure Section wall: Periodic Non-slip at wall
Run Type	Parallel MPI: 6 Core
Mesh	100 000 cells/elements, hexahedron dominant 1 element section thickness

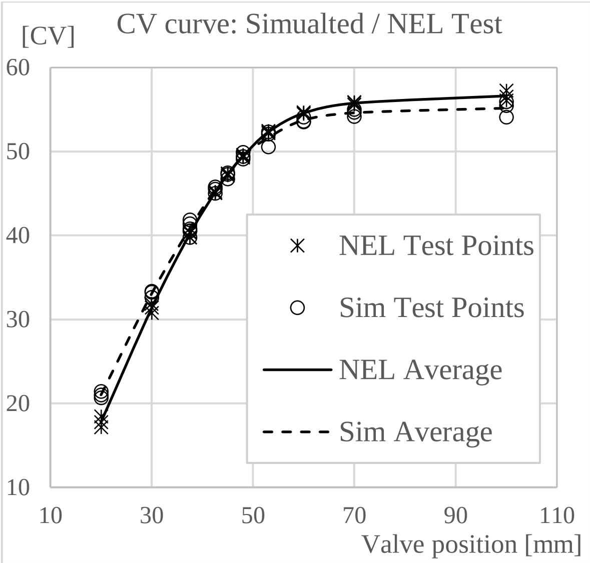

Figure 4. Compared simulation and test results CV values for 33 test points.

Figure 5. Test and pressure port location overview, 2 ID upstream, 6 ID Downstream.

The average difference between simulation and experimental results are found to be 3.1 %. Standards for flow equations for sizing flow control components [9] states an expected accuracy within +-5 %. For global system parameters the CFD code is considered to be an adequate method for predicting capacity as furthermore indicated by A. Davis and M. Stewart [11], [12].

The accuracy and calibration data for the presented experimental measurements are not available. However, the results are considered to be sufficient for comparison of global parameters and system trends.

4. Flow structure and erosion pattern

The objective of the work presented in the following section is to investigate the details of the flow structure through the converging-diverging geometry as shown in Figure 1, with emphasis on the structure downstream of vena contracta. Velocity profiles are used to represent the flow, as indicated in Figure 6, where the velocity profiles are projected onto a typical velocity field for the geometry. Different simulation parameters have been compared in order to investigate the differences in the flow field. For further parametric study of particle trajectories and erosion it is beneficial to reduce the complexity of the simulation model in order to minimize computational time.

Although the magnitude of the flow velocities changes with induced flow rate, the structure is considered to be relatively constant for time averaged two-dimensional representation of a geometry, which for the purpose can be compared with theory and trends from backwards facing step literature. This applies to a wide range of Reynolds numbers in the turbulent flow regime as indicated by Kim [13] and Abbott [14] for similar geometries. A representation of the flow structure through the relevant geometry is shown in Figure 6.

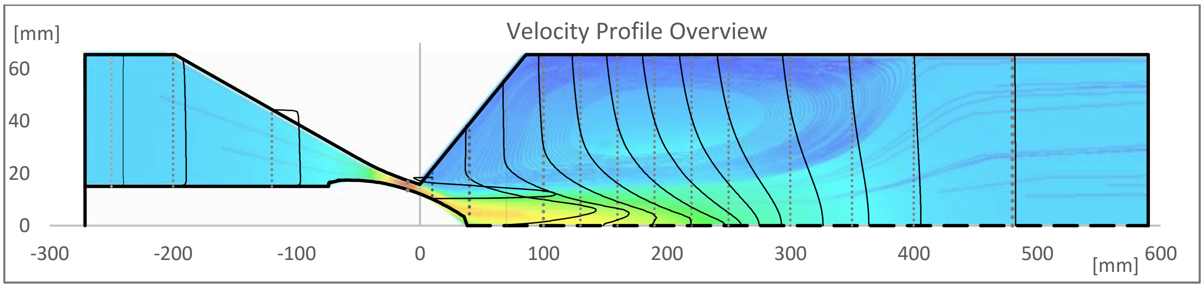

Figure 6. Velocity profile, and flow structure overview, investigational area as indicated in Figure 1.

As erosion is usually calculated based on a flow field to calculated particle trajectories, it is crucial that the flow field is well represented in the simulation. Any discrepancy in velocity, with respect to real life, will cause a significant error in the calculated erosion rate as given by equation (1). Nøkleberg and Søndvedt [2] suggested a geometry with low angles in the converging area of the geometry in order to optimize erosion resistance. Erosion was found to be significantly reduced under test. The remaining challenge is the prediction of erosion in the diverging section where large velocity gradients and high turbulence intensity are observed. It is particularly challenging to predict erosion in such flow conditions, and the erosion is commonly underpredicted [4]. An erosion pattern from a geometry similar to what is investigated in this paper is presented for visual purposes in the figure below. Figure 8 show areas prone to erosion in a relevant geometry prior to and after erosive wear. The erosion test was performed at choked flow, using methane gas based medium with 300 micron quartz particles. Surface geometry was measured before, in intervals and after sand was introduced to the flow. The geometry and measurements from the test is shown in Figure 7 and Figure 8 respectively, which is presented for erosion pattern visualization and for further comparison with flow structure.

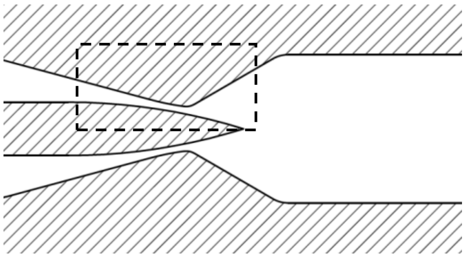

Figure 7. Needle snd seet overview. Overview of investigational area.

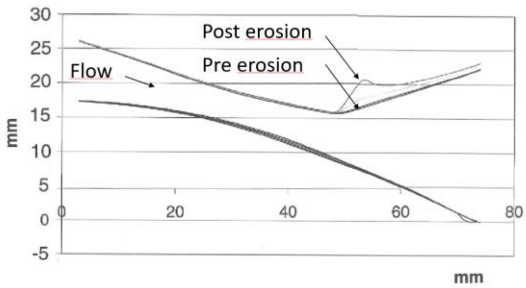

Figure 8. Erosion pattern on stainless steel needle and seat geometry with 15 degree diffuser angle. Reference to investigational area in figure 7.

5. Section geometry, steady state and transient simulation

Steady state simulations can in many cases be considered to be a simplification of transient conditions. For given cases, transient simulations can be presumed to be more accurate with respect to real life as time dependency is accounted for. In the following section, single phase steady state and transient simulations on identical geometries are compared. Simulation parameters are as presented in Table 2.

Table 2. Sectioned geometry, steady state and transient analysis parameter overview.

Parameters	Description
Software	ANSYS CFX
Analysis Type	Steady State, transient (>2 sek real time), single phase
Turbulence model	SST
Geometry Description	2 ID upstream, 6 ID downstream vena contracta
	45 degree, axisymmetric. 15 deg diffuser angle
Fluid	Water, constant properties
Boundary conditions	Inlet: Mass Flow
	Outlet: Average Static Pressure
	Section wall: Periodic
	Non-slip at wall
Run Type	Parallel MPI: 6 Core
Mesh	2 000 000 cells/elements, hexahedron dominant
	20 element thickness

A comparison of velocity profiles is presented in Figure 9 and Figure 10. The distance, location, of the velocity profiles are measured from vena contracta as defined in Figure 6.

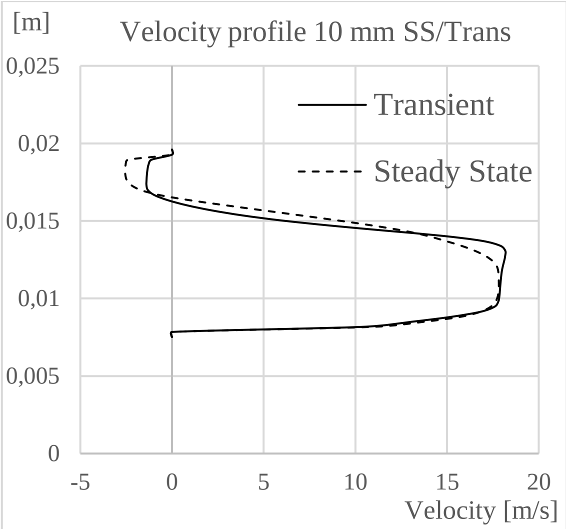

Figure 9. Velocity profile comparison of transient and steady state simulation 10 mm downstream of vena contracta, ref Figure 6.

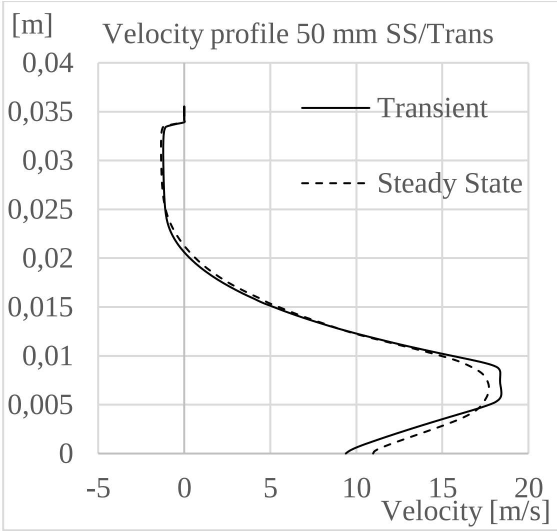

Figure 10. Velocity profile comparison of transient and steady state simulation 50 mm downstream of vena contracta, ref Figure 6.

Figure 10 and Figure 9 show that the velocity profiles from transient and steady state simulations are very similar except in the region close to vena contracta. This is especially prominent in the negative velocity region close to the wall where erosion is observed for these type of geometries as indicated in Figure 8. At position 10 mm, the negative velocity magnitude differs by up to a factor of two. If particles are assumed to follow the flow under these conditions, the erosion rate will be vastly different as calculated by this steady state or transient simulation as equation (1) indicates.

6. Complete axisymmetric, transient simulation

By simplifying the axisymmetric geometry with an angular sliced section, many three dimensional effects may be lost in the simulation. Based on the results presented in the previous section, where the global system parameters are accurately predicted by steady state simulation. It can be hypothesised that the randomness of the movement in the fluid over an infinite amount of time will give a uniform and symmetrical velocity profile. From an erosion point of view, minor fluctuation in velocity profiles of the fluid and particles, in a small time scale is not considered to be particularly relevant. However, it is important to capture all three-dimensional fluid phenomena to investigate the effect on the mean velocity profile for further comparison with sectioned two-dimensional axis symmetric simulations. Thus, a full axisymmetric model, single phase transient simulation was analysed to investigate flow and the time average velocity profiles. Analysis parameters are as shown Table 3.

Table 3. Complete axisymmetric geometry, transient analysis parameter overview.

Parameters	Description
Software	ANSYS CFX
Analysis Type	Transient (10 sek real time), single phase
Turbulence model	SST
Geometry Description	2 ID upstream, 6 ID downstream vena contracta 360 degree, axisymmetric. 30 deg diffuser angle
Fluid	Water, constant properties
Boundary conditions	Inlet: Mass Flow Outlet: Average Static Pressure Non-slip at wall
Run Type	Parallel MPI: 12 Core
No cells	5 000 000 cells/elements, tetrahedron

Figure 11 and Figure 12 show the time average (over 10 second real time) velocity profiles 10 mm and 50 mm downstream of vena contracta. Each location has two velocity profiles representing axis parallel to the view seen in figure Figure 6.

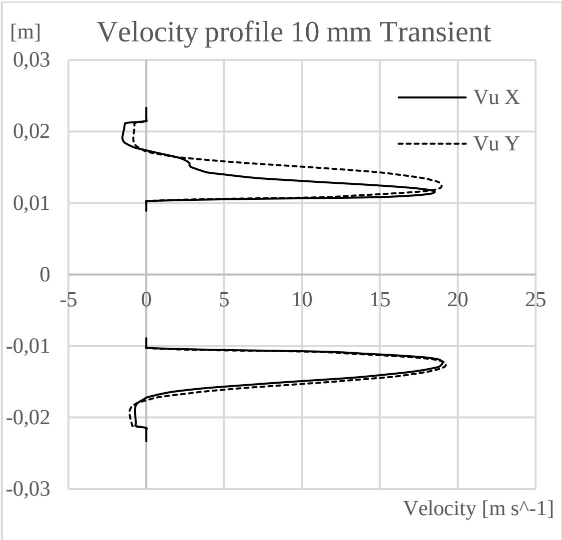

Figure 11. Time average (10 s) velocity profile, in X and Y direction, comparison of transient simulation 10 mm downstream of vena contract, ref Figure 6.

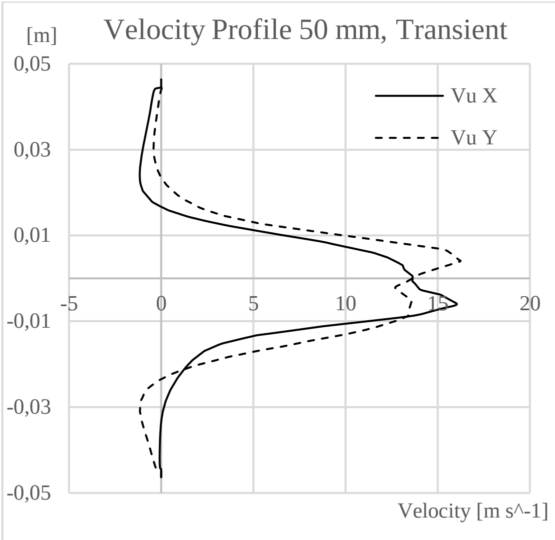

Figure 12. Time average (10 s) velocity profile, in X and Y direction, comparison of transient simulation 50 mm downstream of vena contract, ref Figure 6.

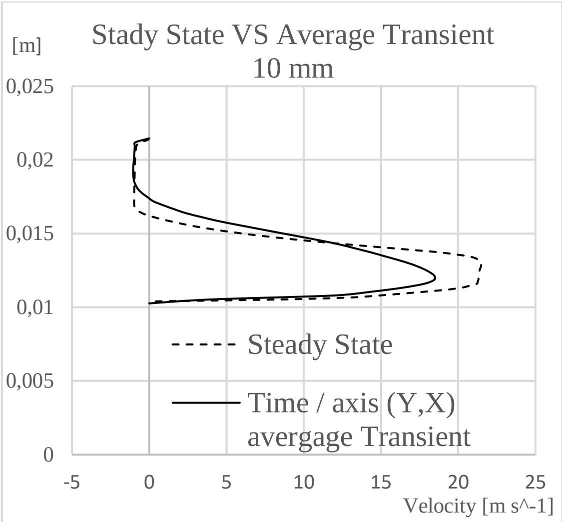

Figure 13. Time and axis averaged velocity profile from transient complete axisymmetric simulation compared with Steady state axisymmetric sectioned velocity profile. "Time/axis (X, Y) averaged transient profile" is the average of Vu X across the Z axis and Vu Y across the Z axis, figure 11, for comparison with a single axisymmetric profile.

Figure 11 and Figure 12 indicates that the velocity profile is not symmetrical over the time period of the simulation. The average standard deviation for the profile as presented in Figure 11 and Figure 12 is 0.56 m/s and 1.41 m/s respectively. Figure 13 presents a comparison of a velocity profile from a sectioned steady state simulation and a time averaged, axis averaged (from both Y and X parallel) transient velocity profile. The discrepancies are identified as significant both with respect to gradients and overall magnitudes. However, in the negative flow region close to vena contracta where erosion is observed as indicated in Figure 8, the three dimensional effects of the turbulent flow become less prominent and the discrepancy between averaged transient and steady state is reduced compared to profiles further downstream of vena contracta.

7. Conclusion

Simplified numerical models predict the global parameters sufficiently, within an average of 3.1 % compared with experimental results. For the given geometry, simplified numerical models as presented can be used to properly size geometries for specific applications

Simulation simplifications is a powerful mean of reducing computational time to cover a greater range of parameters within a parametric study. Hence, steady state, and transient simulation results were produced and compared. In addition, geometrical simplifications such as sectioning of an axisymmetric model were compared with full axisymmetric model.

Steady state and transient simulations for identical sectioned geometries were compared. The results show similarities in velocity profiles but the discrepancy between simulations become prominent in the negative velocity region just downstream of vena contract, where erosion is observed. As erosion models are sensitive to the velocity of particles, and hence fluid velocity, the discrepancies can cause large errors in the erosion rate prediction.

The complete axisymmetric transient simulation show large variation in velocity field as a function of time as expected due to the large turbulence intensity. Furthermore, the time averaged velocity profile is not symmetrical over the simulation period. The comparison of the time and axis averaged results from the complete axisymmetric transient simulation and simplified steady state show large general discrepancy, however, good correlation in the regions of interest downstream of vena contracta.

In order to verify the velocity profiles and selected simulation simplifications, experimental data is required. When detailed numerical analysis can be compared with experimental data, it is believed that any factor adding to discrepancy between results may be identified. Furthermore, a justified correction can be made to the models, or parameters, in order to achieve a more accurate erosion prediction for the specific geometry.

8. Future work

The results presented in this paper show good correlation between available experimental data and numerical data. However, for details regarding the flow structure downstream of vena contracta, it is not conclusive. The differences in the velocities near vena contracta are as much as two times between steady state and transient simulation, resulting in potentially up to eight times (n=three) erosion rate as indicated by equation (1). The large discrepancy becomes challenging with respect to component lifetime prediction. In order to compare the simulated results further, laboratory test have to be completed for this specific geometry. Future work will revolve around experimental setup and comparison of experimental and numerical results, based on the simulations and methods as presented in this paper.

Table 4. Nomenclature.

Parameter	Description	Unit
$\dot{E}$	Erosion rate	[mm / year]
$\dot{m}_p$	Mass flow rate of sand	[kg / s]
K	Material constant	
U_p	Particle velocity prior to impact	[m/s]
$F(\alpha)$	Material function	
CV	Flow Coefficient	
Q	Flow rate	[gallons/min]
SG	Specific gravity	
P	Pressure	Psi
ρ	Density	[lb/ft^3]
N	Conversion factor metric / imperial	
n	Particle velocity exponent, material dependent	

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