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Solid Particle Erosion in Contraction Geometries: Development and Validation of a CFD-Driven Model

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Abstract

Erosion in oil and gas production systems in critical components like choke valves featuring contraction geometries poses significant operational and economic challenges. The high-velocity and accelerated solid particle-laden flows in contractions result in material degradation, diminished equipment lifetime, and serious safety risks. The main goal of this study is to develop and test a robust erosion model using Computational Fluid Dynamics (CFD) that can accurately predict erosion in these challenging geometries. A three-step CFD analysis method was adopted, modeling the flow of fluids, tracking particles, and quantifying the erosion wear. Various parameters have been examined, such as fluid velocity, particle size and concentration, and most importantly, how different contraction ratios affect erosion rates. The model developed for the first time in the industry and has been checked against experimental data to ensure its predictability. The results of this study will help improve the design and operation of choke valves with contraction geometries. This will lead to longer component lifespans, lower maintenance costs, and better system reliability in environments that cause erosion.

1. Introduction

In oil and gas production, positive choke valves are fixed-orifice devices that control flow rates and stabilize wellhead pressure. They control flow with interchangeable choke beans, which are precision-drilled inserts with specific orifice sizes (usually measured in 1/64-inch increments) [1]. Changing the bean lets operators change the flow rate without having to change the valve body. The popularity of these valves comes from their simplicity, reliability, and ease of maintenance, but they can wear down easily due to the inherent shape that features a contraction where accelerated flows with abrasive particles like sand cause high erosion rates. Erosion can damage the choke bean and the inside surfaces, which can cause problems with performance or even failure [2].

Various research has been conducted to study erosion in this shape; Blatt et al. [3] used a sudden expansion tube as a geometry to study the effect of hydrodynamics on the erosion corrosion process. They found that the maximum metal loss due to erosion occurred at a distance of 2 to 3 times the tube diameter downstream from the constriction. Their findings have been demonstrated by plotting the radial flow velocity measured by Laser Doppler Anemometry (LDA), which shows a peak at this distance. This phenomenon correlated well with field cases where erosion in chokes can occur downstream of the choke, as reported by Shawn [4]. Results in Blatt et al. [3] correlated well with Stieglmeier et al.'s [5] findings. They have used diffusers with different angles and found that the maximum turbulent energy occurred at a certain distance downstream from the expansion, and its peak is higher in the case of lower angles. Sekti et al. [6] studied the effect of sand erosion in sudden expansion and concluded that large expansions are less prone to erosion. Moreover, in an attempt to enhance the CFD erosion rate prediction, they have used the particle size distribution rather than the mean particle size. However, they noticed just a slight improvement in the calculations. Badr et al. [7] tested the effect of impingement velocity and particle size as well as the flow direction on the erosion rates for sudden contraction. They concluded that erosion rates are strongly dependent on velocity and particle sizes and less dependent on the flow direction except for low velocities and big particle sizes. Results showed a threshold velocity of 2 m/s below which erosion rates are insignificant. Nemilatalla et al. [8] studied the effect of flow velocity and particle size on erosion downstream of an orifice. In contrast to previous studies, which highlighted only one erosion pick downstream expansion, they have noticed two erosion picks downstream of the orifice, one in the separation zone and the second in the reattachment zone. They observed that erosion downstream of the orifice increases with increasing inlet velocity and decreases with increasing particle sizes and explained the latter phenomenon by the fact that the gravity effect is more dominant in the case of low velocities.

Nowadays, CFD is commonly employed to model erosion in chokes and contraction geometries. Alister et al. [9] emphasized the role of CFD in accelerating the choke design evolution, which is traditionally done in the trial-and-error form. They detailed the procedure of building a CFD model for erosion calculation and concluded that CFD simulations in predicting erosion location and intensity are in agreement with experimental results. Asmund and Oddmund [10] explained a method to use CFD and experiments to develop erosion models, and they did a comparison between experiments and CFD for simple and complex geometries such as Bend, Multi Orifice Valve (MOV), and Bean choke. They explained the difficulties in fully obtaining the experimental results due to the complications in modeling the fluid and particle flow for complex geometries. They included examples to demonstrate how erosion models, such as the DNV model, can predict experimental data to a certain degree. Mclurry and Shirazi [11] simulated the bean choke erosion using compressible fluid (methane). They found that the maximum penetration will occur at the outlet of the contraction and that an enhancement in the inlet and outlet geometry will decrease the turbulence and reduce the erosion as well.

Furthermore, NØkleberg and SØntvedt [12] studied the effect of erosion in different choke types (needle and seat as well as external sleeve valve). The used model predicted results 2 to 3 times lesser than the experiments results, which was an accepted erosion error based on the author. The author investigated the choke erosion in different components of the valves, and they concluded that in all cases there is an erosion peak at some distance downstream from the valve. Zhang [13] studied erosion in contraction-expansion geometries caused by small particles and emphasized several limitations of CFD models to predict accurately material erosion, such as inaccuracies in particle-eddy interaction modeling, that might lead to higher erosion rates caused simply by unphysical particle impacts. Many in-depth numerical studies have been conducted to examine the effect of various parameters on erosion of contraction expansion geometries [14], [15].

CFD has become an important tool to study flow-induced erosion, especially in complex geometries like choke valves. Experimental methods are usually accurate, but they can be limited by cost, size, and accessibility, especially in environments with high pressure and temperature or when submerged. Jun et al. [16] and other studies have shown that CFD can reliably predict erosion in jet impingement scenarios with adequate grid refinement and wall treatments. In the same way, Raghavendra et al. [17] used CFD to model erosion rates in choke valves under very harsh service conditions. Their results showed that CFD can be used to predict wear zones where direct measurements are not possible. Ling et al. [18] also used CFD to look at how the size of sand particles and the opening of a valve affect erosion patterns. This is important information for improving the design of HPHT valves. Lise's [19] study backed this up by using CFD to model how erosion spreads in multiphase pipe flow, which would be hard to do in real labs.

Despite numerous experimental studies on contraction geometries, there is still a large gap in the development of specific erosion prediction models for positive choke valves and contraction geometries. The NDV [20] model, which is specifically designed for reducers with gradual contractions and does not generalize well to sharper or more abrupt contraction profiles, is notably the only model that is currently available that addresses contraction-type geometries. Furthermore, although the University of Tulsa has incorporated a proprietary erosion model for contraction geometries into their Excel-based SPPS software, the model is not open-source, and its internal workings are still unknown, which restricts its applicability for wider scientific extension and validation. Given these gaps, this work aims to develop a robust and reliable erosion model designed specifically for abrupt contraction shapes by leveraging the capabilities of computational fluid dynamics (CFD) and current general-purpose erosion models. In addition, the study suggests a new model to predict erosion behavior downstream of the contraction, a crucial area where most of the pinhole leaks usually happen and where no specific model is yet available. This contribution improves the predictive understanding of erosion in positive choke valve configurations and fills a significant gap in the industry.

2. Numerical Modeling

Ansys Fluent was used to model the particulate flow and simulate erosion in contraction geometries. The k-ε turbulence model and the scalable wall function were adopted, and a velocity inlet boundary was imposed with varying velocities, which gave a Reynolds range from 2.5e4 to 1e6, while the outlet was set to a pressure outlet. Walls were treated as smooth, no-slip stationary walls, while an axis boundary was imposed at the symmetry of the 2D geometry. Once the flow field of water was simulated, a sufficient number of particles were injected, and erosion on the walls was collected based on the McLaury erosion model [21].

2.1 Simulated Geometry

For simplification and ease of computation, a 2D axisymmetric geometry was used; moreover, this geometry gave a comparable result to 3D models based on a study conducted by Baghdadi et al. [22]. The geometry of the specimen used in this study is shown in Fig. 1 with various contraction ratios that have been modeled during this study.

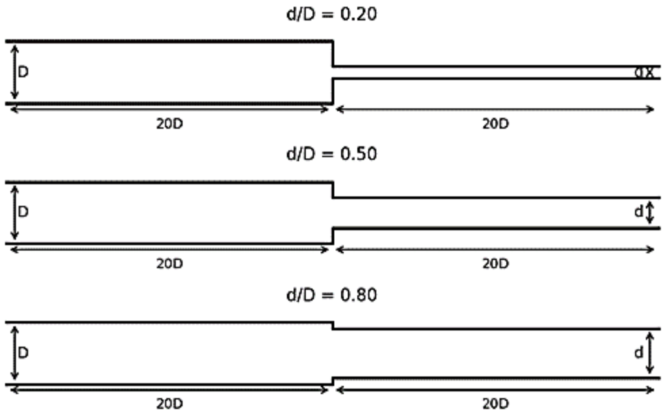


Fig. 1 *Simulated geometry (contraction ratios 0.2,0.5 and 0.8)*

2.2 Grid Dependency Test

A structured mesh was created using the Ansys mesh. The mesh has 40 elements per diameter length horizontally, while the number of radial divisions was varied from 20 to 100 to check the impact of the mesh size on the simulation results. Two velocity points are located at the centerline and at a distance of 0.5D and -0.5D from the contraction step, i.e., one in the inlet region and the other one in the contraction region. The location of two points was chosen in order to see how the divergence of the flow towards the contraction while the second one was to check flow acceleration in the contraction section. The velocity at both points is shown in Fig. 2. A stable trend is observed from 80 divisions onward.

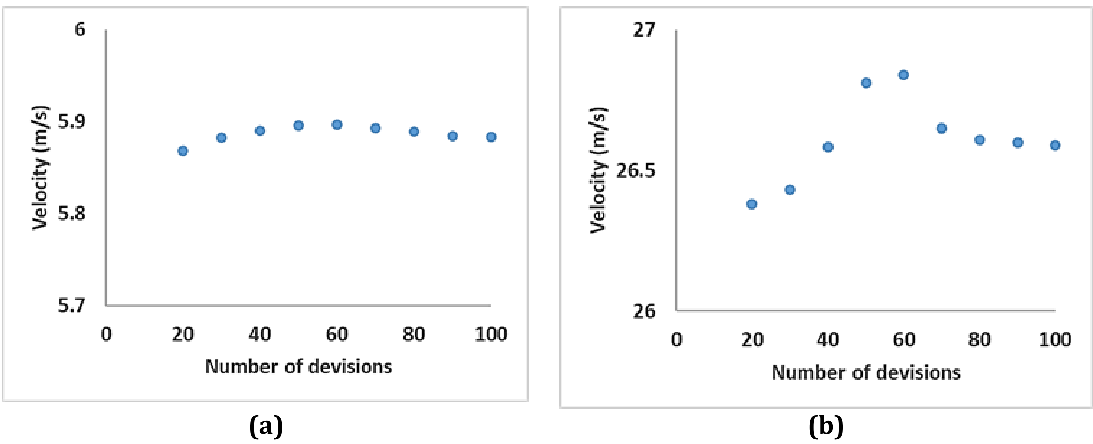


Fig. 2 *Effect of mesh size on simulation results (a) Point in the inlet section; (b) Point in the contraction section*

As the main objective of the CFD runs is erosion simulation, another sensitivity on the mesh size effect on the maximum erosion rate is shown in Fig. 3. Similar to the velocity profiles, the erosion rate stabilized at any mesh with more than 80 radial divisions, which concludes that a mesh with 80 radial divisions will be enough to ensure stable CFD results.

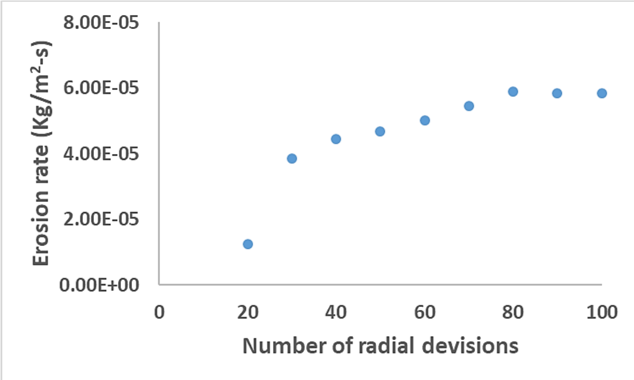


Fig. 3 *Variation of maximum erosion rate on face step with mesh size*

2.3 Wall Function and Near Wall Treatment

To minimize the effect of mesh size on the simulations, especially the effect of the first cell height on erosion rate, equal mesh sizes were adopted for all geometries, ensuring that the first cell height is of the same dimensionless magnitude across all geometries as the number of radial divisions is kept constant. For wall function selection, the y+ magnitude for all cases was plotted in a histogram as shown in Fig. 4, where most of the values fall between the 30 and 300 range, indicating it's suitable for the standard wall function. However, since around 13% of cases will have a y+ below 30, the scalable function was favored to overcome the strict requirement of the standard wall function of y+>30.

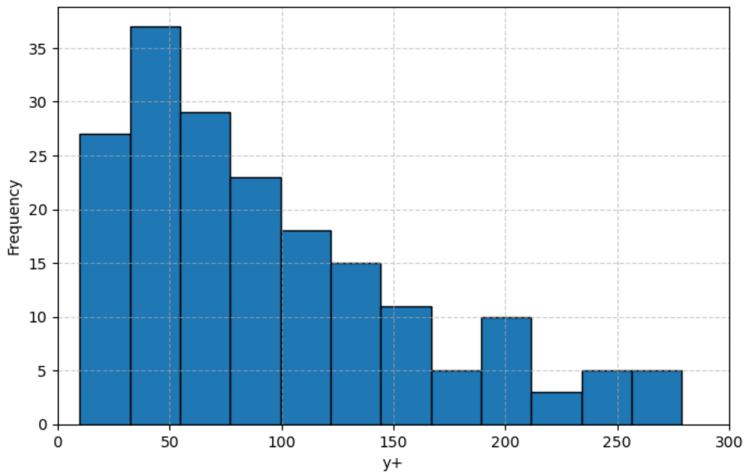


Fig. 4 *y+ distribution for all simulation cases*

2.4 Discrete Phase Modelling (DPM) for Particle Tracking

As part of erosion prediction, DPM was implemented to track a sufficient number of particles and collect their impact information, such as impact angle and velocity, which are necessary inputs for the erosion model. In the current study, 100000 particles were injected for each simulation case to have representative erosion profiles. Fig. 5 shows part of the particles tracked in the geometry, which directly impinge on the contraction step and again downstream at a certain distance. The current study will model the erosion at the contraction step as well as downstream of it at the contraction section. The number of injected particles was chosen to have a stable erosion rate, and for that various numbers of particles were injected, and the maximum erosion rate was recorded and plotted in Fig. 6. As it can be seen after a sufficient number of particles have been injected, the erosion rate starts to stabilize; in this case, any number of particles greater than 70000 particles will ensure a stable erosion rate, and for the current study, 100000 particles have been chosen.

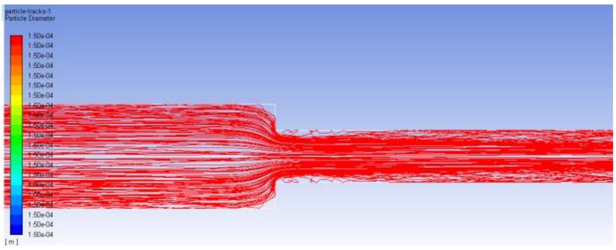


Fig. 5 *Particles tracking (80 particles illustrated)*

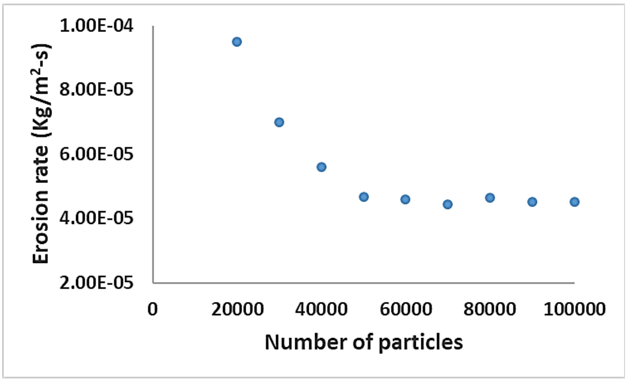


Fig. 6 *Variation of maximum erosion rate with number of particles injected*

2.5 Convergence Criteria

Residual plots for continuity and momentum equations were set at 10 E-6 for all residuals to monitor convergence as shown in Fig. 7.

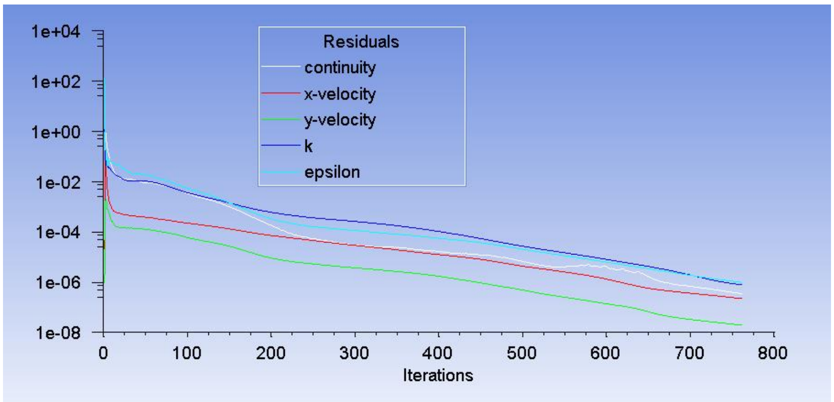


Fig. 7 *Residuals plot*

2.6 Flow Visualization

Fig. 8 shows the velocity magnitude contours plot. It can be clearly seen how the flow diverges and accelerates towards the contraction. This flow divergence and accelerated velocities inside the contraction area is responsible for high erosion rates in these geometries as it will be discussed later.

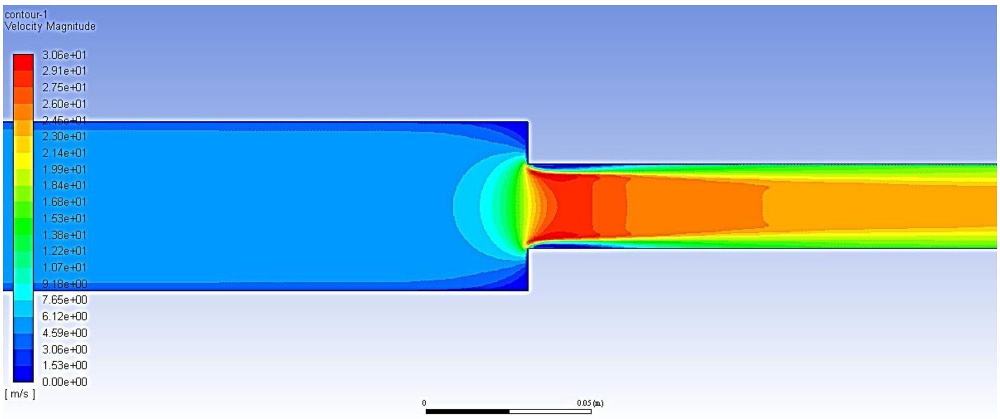


Fig. 8 *Velocity contour plots*

3. Data Set Preparation

Accurate regression analysis requires a sizable and representative dataset to create a trustworthy empirical model. This makes it more likely that the model will be able to depict the main patterns and behaviors of erosion under various flow conditions. Various cases were simulated in this study. In particular, there were four pipe diameters, seven contraction geometries (narrow to wide), five particle sizes, and seven velocities. A comprehensive erosion profile was produced for each of the 980 simulation cases that were created by combining all these parameters. The dataset used to create and validate the new erosion model using regression techniques consists of these 980 erosion profiles. The selected cases allow for inlet Reynolds numbers up 2.5e4 to 1e6 and velocities inside the contraction up to 300 m/s, which covers a wide range of operation conditions in oil and gas. Table 1 show the CFD simulations matrix.

Table 1 *CFD simulations matrix*

Features	Number of cases	Cases
Inlet diameter (in)	4	1, 2, 3, 4
Contraction ratio (d/D)	7	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8
Inlet velocity (m/s)	7	1, 2, 3, 4, 5,7.5,10
Particle size (microns)	5	25,50,100,150,300

4. Results and discussion

4.1 Erosion Modeling

As mentioned earlier, the DPM module in Ansys Fluent will be used to track the injected particles with various sizes and collect their impingement parameters, mainly the impact angle and impact velocity. Those parameters are injected into the McLaury erosion model to predict the erosion rates at the step of the contraction and downstream in the contraction.

4.1.1 McLaury Erosion Model

As described in Brenton et al. [21], this model has the general form of,

$$ER = A\, v^n\, f(\theta) \tag{1}$$

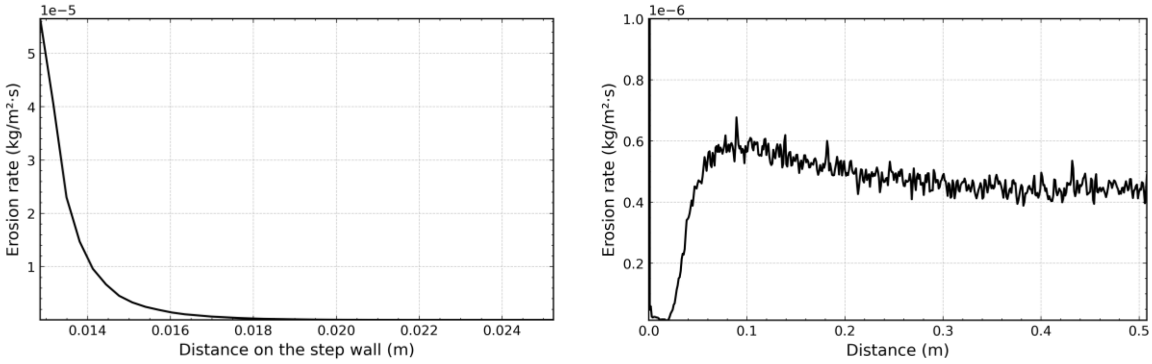
where ER is the erosion rate, A and n are constants where A takes the value of 2.388×10^{-7} for aluminum and n a value of 1.73 which is representative for various materials, V the velocity and f a function of θ which is the impact angle and expressed as follows for aluminum:

$$f(\theta) = \begin{cases} -34.79\theta^2 + 12.3\theta & \theta \leq 10 \\ 0.147\, cos^2\theta\, sin(5.205\theta) - 0.745\, sin^2\theta + 1 & \theta > 10 \end{cases} \tag{2}$$

It is to be highlighted while in the current study the CFD based model will be built upon McLaury erosion model, same approach can be applied for other models to build the CFD based erosion model.

4.1.2 Erosion Profiles

This study will not focus only on the erosion of the sharp step but will extend the modeling for downstream in the contraction section, where so far, the industry lacks this model, and most of the leaks encountered in industry happen at that location. Fig. 9 shows both erosion profiles on the step and on the contraction part downstream of the step. From the erosion profile on the step, it can be clearly seen that the max erosion is happening at the sharp corner of the step, where most of the particles will deviate following the contracted flow and hit that corner, whilst the max erosion in the contraction occurs at a certain distance downstream.



(a) **(b)**

Fig. 9 *Erosion profile (a) The step wall; (b) The outlet wall (contraction section)*

4.2 Erosion at the Contraction Section

As explained earlier, this study will examine the impact of various parameters, such as flow and particle properties, on the erosion rate and develop an erosion model subsequently.

4.2.1 Effect of Velocity

As can be seen in the McLaury erosion model, velocity is one of the dominant parameters of the erosion rate, where the erosion rate increases exponentially with increasing velocity. A similar observation in the contraction geometry is shown in Fig. 10, where the erosion rate increases with increasing velocity. It is to be highlighted that in Fig. 10, each point represents the maximum erosion rate simulated at the contraction session.

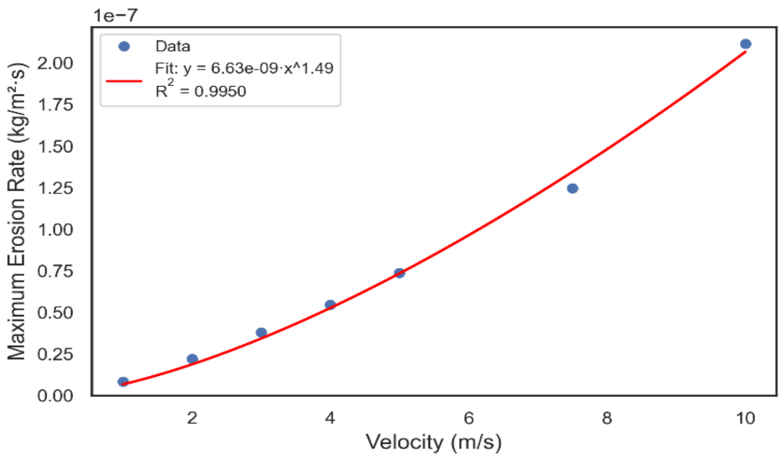


Fig. 10 *Effect of velocity on the maximum erosion rate*

4.2.2 Effect of Contraction Ratio

In In this study, the contraction ratio is defined as the ratio between the contraction diameter and the inlet diameter (d/D); hence, a higher contraction ratio represents a mild narrowing, and a lower contraction ratio represents a tight throat. It is very clear from Fig. 11 that tight throat contractions are more prone to erosion, which might be explained by the accelerated flow in narrow passages.

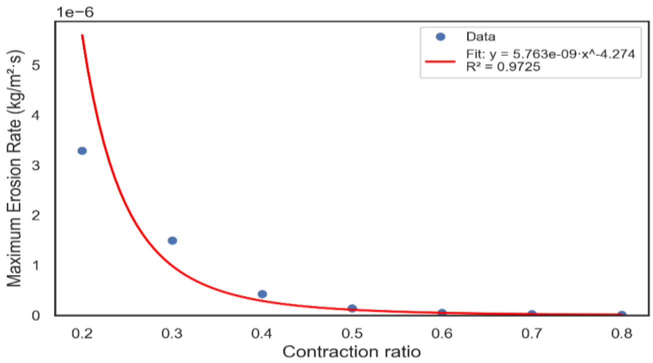


Fig. 11 *Effect of contraction ratio on the maximum erosion rate*

4.2.3 Effect of Inlet Diameter

It was observed that at constant flow and particle parameters and at the same contraction ratio, increasing the inlet diameter will result in decreasing erosion rates as shown in Fig. 12. The finding might be explained by the fact that at a constant contraction ratio, increasing the inlet diameter will increase the height of the step, and hence, at constant particulate flow properties, this large step will receive less particle deposition per unit area, which will result in less erosion.

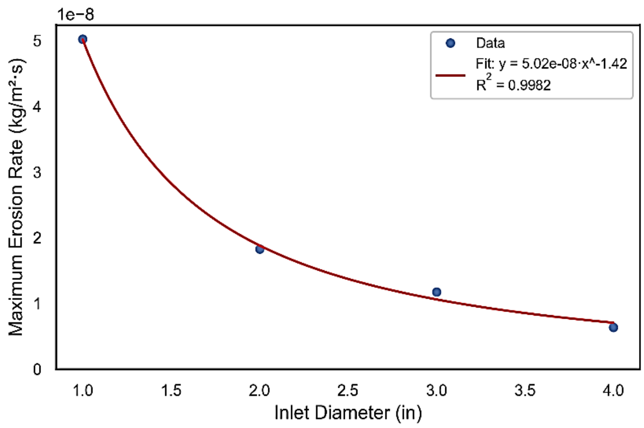


Fig. 12 *Effect of inlet diameter on the maximum erosion rate*

4.2.4 Effect of Particles Size

The particle size was found to have a reverse effect on erosion rate at the contraction as shown in Fig. 13. Big particles were found to produce less erosion, in contrast to other shapes like bends and tees, where bigger particles cause higher erosion. This study's results agree with the findings in Zhang [13], which showed in some tests that small particles lead to more erosion in contraction shapes, and this was also noted by Alister et al. [9].

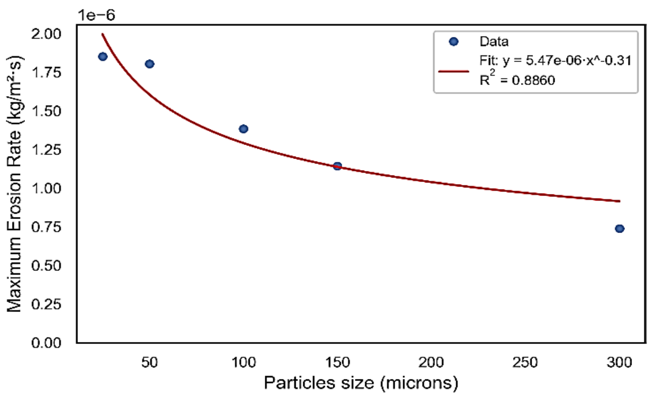


Fig. 13 *Effect of particles size on the maximum erosion rate*

4.2.5 Effect of Sand Rate

The sand rate is a scale factor, as shown in DNV [20] and other models. Even though the sand rate was not part of the data matrix, a few cases have been run to check the effect of the sand rate, and results are shown in Table 2 for one of the simulation cases. As can be seen, the ratio of erosion rate to erosion rate is similar to the ratio between successive sand rates, which is another confirmation of the effect of sand rate that could be used as a multiplier. In the current study, the erosion rate will be modeled using the earlier discussed parameters, and sand will be used as a multiplier. Knowing that the reference sand rate used to generate the simulation cases is fixed at 1 g/s.

Table 2 *Effect of sand rate on erosion*

Sand rate (kg/s)	Max erosion rate (Kg/m^2-s)	Sand rate to sand rate ratio	Erosion rate to erosion rate ratio
0.001	3.49E-07		
0.01	3.49E-06	10	10
0.1	3.49E-05	10	10
1	34.93-04	10	10

4.2.6 Model Development

As can be seen in Figs. 10 to 13, most of the effect of various parameters can be matched to a power law of the form Er_max = a*x^b, where Er_max is the maximum erosion rate, a and b are constants, and x is a holder for one of the variables discussed earlier, such as velocity and particle size, and so on. Hence, a general model with the same form is highly likely to fit the data. A regression was conducted on 980 points representing the max erosion point for each simulation case, and the fitting result is shown in Fig. 14. Despite the good fit obtained and the coefficient of correlation R2=0.98, which shows high correlation, there are still some points, mainly at high erosion rates, that exhibit some deviation from the model; however, the errors are within 10%.

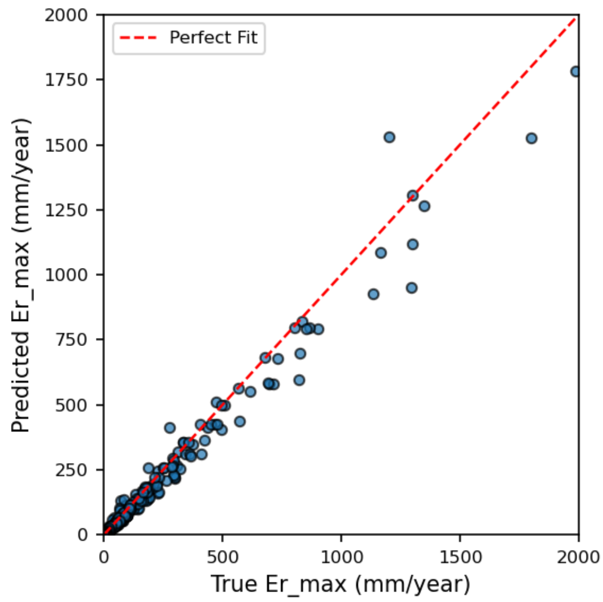


Fig. 14 *Predicted versus true erosion rate*

The final model has the following form:

$$Er = 1.145\ 10^{-6} * S * V^{1.619} * D^{-1.615} * R^{-5.075} * {d_p}^{-0.45} \quad (3)$$

where Er is maximum erosion rate at the contraction section (mm/y), S is sand rate (g/s), V is fluid inlet velocity (m/s), D is inlet diameter (m), R is contraction ratio (d/D) and dp is articles size (m).

4.3 Erosion at the Face Step

Similar work has been conducted to model erosion at the step face. The final model is shown in Eq. (4) and the fit curve is shown in Fig. 15. Despite the good fit and an R^2 = 0.985, the analysis shows some deviations at higher erosion rates, similar to the observation made for the contraction; however, all deviations are under 10%. It is to be highlighted that this erosion rate will hold valid for the initial condition before erosion causes higher metal removal and shape change for the contraction, which will affect the flow and subsequently the erosion rate. However, the model still offers significant advantages by providing this erosion rate and giving an indication of how quickly the contraction will initially erode. Additionally, for high-resistant materials, even though their model is not developed in the current study, in cases of coated valves or solid body materials, this model will hold correct for a long time, as these materials have a very low erosion rate and shape change will not occur quickly.

$$Er = 1.398\ 10^{-4} * S * V^{1.78} * D^{-1.48} * R^{-4.715} * d_p{}^{-0.417} \quad (4)$$

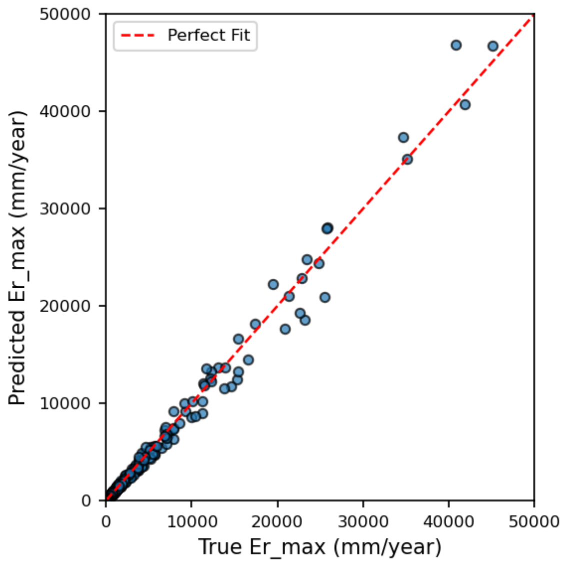


Fig. 15 *Predicted versus true erosion rate*

4.4 Carbon Steel Erosion Model

Similar work has been done for carbon steel using McLaury model developed for carbon steel as described in [21]. The contraction erosion model is shown in equation 5 while the erosion model for the face step is shown in Eq. 6.

$$Er = 3.045\ 10^{-7} * S * V^{1.586} * D^{-1.574} * R^{-4.88} * d_p{}^{-0.472} \quad (5)$$

$$Er = 4.68\ 10^{-5} * S * V^{1.792} * D^{-1.525} * R^{-4.622} * d_p{}^{-0.367} \quad (6)$$

4.5 Model Validation

In this section the predicted erosion rates by the model will be compared against some published experimental data.

4.5.1 Validation of the Erosion Model for Aluminum Material

The first experiment was conducted by McLaury et al. [23], where aluminum was used to evaluate the impact of geometry change on erosion rates. A water-laden flow was flowed at 2.9 m/s with a sand concentration of 2% and a particle size of 155 microns. The inlet of the geometry has a diameter of 15.9 mm (0.625 in) and the contraction a diameter of 6.5 mm (0.255 in), resulting in a contraction ratio of 0.408. As can be seen in Fig. 16, the erosion rate predicted by the developed model for the contraction section is slightly higher than the experimentally recorded erosion rate in [23], with about a 13% difference. Actually, this difference might be explained by the fact erosion is decreasing with time, as demonstrated in the same study. This shows the good prediction of the developed model inside the contraction session, where this model has been developed for the first time in industry.

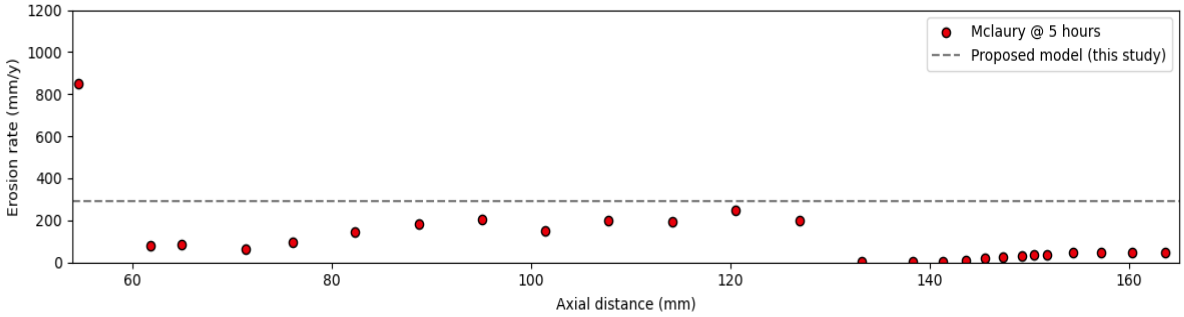


Fig. 16 *Predicted versus experiment erosion rate*

The erosion rate at the step wall was reported as well in [23]; however, it was very low in comparison with the currently developed model: 850 mm/y in the experiment vs. 13000 mm/y predicted by the current model. The experiment erosion model was reported after 5 hours, where some rounding had already occurred at the edge of the contraction, which is known to drastically reduce the erosion rate. Moreover, the erosion rate reported by the experiment was based on the weight loss of wafers, which is an average metal loss along all the walls of the contraction, which is not representative of the hot spot located at the corner of the contraction, which was modeled by the current study as the maximum erosion rate; hence, a straight comparison can't be completed.

4.5.2 Validation of the Erosion Model for Carbon Steel

Postlethwaite and Nesic [24] conducted an experiment on contraction geometry made of carbon steel. The contraction geometry has an inlet of 42.1 mm and an outlet of 21.2 mm, giving a contraction ratio of 0.504. Water with silica sand of 430 microns in size at a 5% concentration was flown at a speed of 3.3 m/s, and erosion rates were recorded as shown in Fig. 17. The erosion rates reported by Postlethwaite and Nesic [24] are shown as a continuous injection trend; however, since a further investigation by the author indicated that the changing of sand a few times will result in higher erosion rates explained by the rounding of the sand particles due to repeated impacts, we have used the factor 2 found in the study to have representative data to be compared with our model without being impacted by particle rounding. The maximum erosion rate predicted by the model is on the higher side, which is physically logical, as the model is predicting the initial erosion rates, which are known to be reduced with time due to rounding of the geometry.

Subsequently, the predicted model erosion rate is evaluated at 198 mm/y, while the maximum erosion rate from the experiment is 150 mm/y, which is again a good indication about the predictability of the model since the experimental rate was recorded after 2 hours, and some material removal and rounding would have already reduced the initial rate. The erosion model developed for the step face predicted 12400 mm/y, while the one from the experiment was around 2500 mm/y, which is almost 5 times. As explained earlier for the case of the aluminum experiment. It used a weighted average of metal loss on the wall of the step, which is not representative of the max erosion rate on the step. This remains a weak procedure, and new methods to measure this max rate might need to be developed.

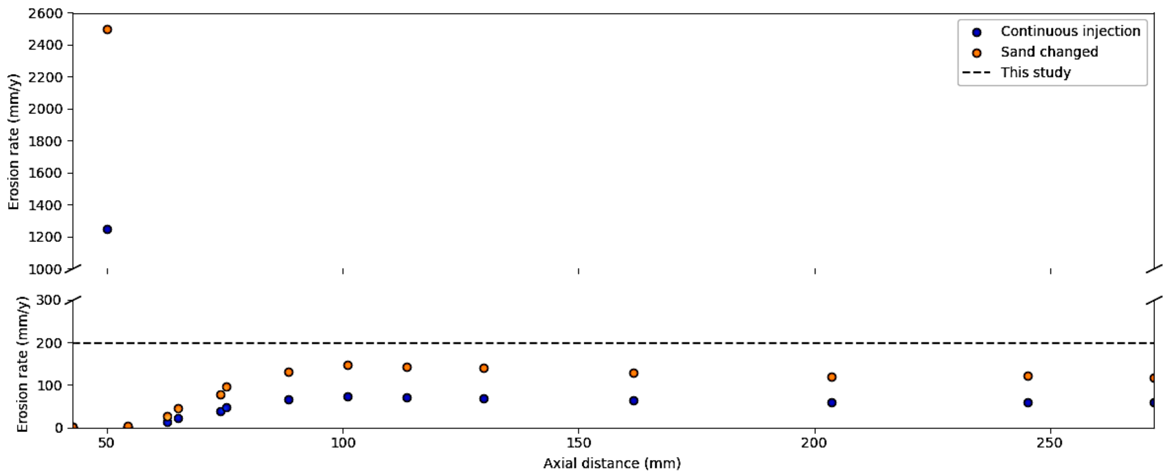


Fig. 17 *Predicted versus experiment erosion rate*

5. Conclusions

In this study a CFD-based erosion model was developed for positive choke valves featuring sudden contraction geometry. Notably, this work introduces for the first time a novel erosion model for the contraction section of the choke, which has not been modeled before in the industry. Moreover, the model accounts for erosion on the step region, giving a holistic view of the erosion-prone regions in contraction geometries. The model was developed for both aluminum and carbon steel material, covering a broad range of engineering applications. Moreover, the same procedure presented in the study can be applied for different erosion models and evaluating different materials. The model validation was carried out against experimental data for both materials, aluminum and carbon steel, which shows good agreement and shows the high predictability of the model.

This CFD-based erosion model represents a significant advancement in the predictive analysis of erosion in choke valves. It serves as a robust tool for design and a valuable tool in operational monitoring and surveillance. Its implementation can support proactive maintenance strategies, reduce unplanned downtime, and improve the overall reliability and longevity of critical flow control components in high-erosion environments.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used [quillbot.com] in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Faical Baghdadi, Meftah Hrairi;* ***data collection:*** *Faical Baghdadi;* ***analysis and interpretation of results:*** *Faical Baghdadi, Meftah Hrairi, Waqar Asrar;* ***draft manuscript preparation:*** *Faical Baghdadi, Meftah Hrairi. All authors reviewed the results and approved the final version of the manuscript.*

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