Influence of flow limiter and grain shape factor of sand particles on erosion activity in pipeline

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Abstract. Erosion has been evaluated as the main cause of failure in pipework. The focus of this work is the effect of erosion activity on two-phase flow (solid-liquid) condition. Pressure distribution of liquid flow, velocity profile of liquid flow and trajectories of sand particles are scrutinized. Based on the experimental data, different limiter pipeline was simulated to validate the data and an overall grain shape factor of 0.265 was obtained. From the qualitative and quantitative analysis of grain shape factor (GSF), it was identified that the 75% of sand are composed of high sphericity particles (GSF=0.2), 25% of sand composed of slightly lower sphericity particles (GSF=0.45). For the simulation work, the fluid flow rate, grain shape factor and sand concentration is altered ranging between 25 litres/s to 50 litres/s, 0.2 to 1.0 and 0.5 % to 1.0 % respectively. Through ANOVA analysis and it demonstrated the significant influence on erosion activity in descending order (fluid flow rate > shape factor > sand concentration). After numerical optimization, the minimum erosion activity on limiter was obtained by obeying the settings of fluid flow rate, shape factor and sand concentration as 50 litres/s, 0.2 and 1.0 % respectively.

1. Introduction

In the oil and gas industry, transportation of fluids during production is normally entrained with solid particles. The sand production in pipelines is one of the main contribution to erosion, thus it has been scrutinized as the cause of pipe work failures [1]. The solid particle found in pipeline is originated from sandstone where oil and gas is extracted. The presence of this sand particle has been a common issue in the oil and gas industry [2]. There are some areas inside the pipeline which are more susceptible to erosion, such as integral parts, elbows, plugged tees, choke and choke valves [3]. There are many preventive measures taken to minimize the erosion problem. For instances, the use of gravel packs and sand screen to remove the sand particles in the fluids [3]. However, these two equipment could not prevent smaller sand particles from flowing into the pipeline. In order to resolve this problem, researchers have been using an assortment of models and approaches to study the erosion process. Among empirical, mechanistic and computational fluid dynamics (CFD) approaches, this work is focusing on CFD approach to investigate the controlling parameters as well as easy visualization of erosion process. With the help of this theoretical
In this present work, STAR CCM+ will be used to study the changes in erosion rate based on different studied parameters. The impact location of the sand particles and its velocity are strongly related to the fluid flow phenomena [3]. CFD’s approach is widely used as it enables researcher to study the areas of interest that is prone to erosion, in particular of a complicated geometry that is difficult for researcher to collect the erosion’s data from or to set-up the experiment [4]. Generally, CFD-based erosion modeling involves three main steps, namely (i) flow modeling, (ii) particle tracking, and (iii) the information of particles that are going to impact on the wall pipeline [5]. Due to the fact that CFD can simulate a real fluid flow and also able to complement with experimental approaches, it is considered as a cost-effective means of tool [6]. Researchers are attempting to tackle this erosion problem from both experimental and theoretical approaches [7,8]. Due to difficulties in building industrial-scaled transportation piping, theoretical simulation has gained much attention recently. However, based on the state-of-art technologies, commercial computational fluid dynamics (CFD) software such as STAR CCM+, COMSOL and Fluent also have their own drawbacks in simulating erosion activity in pipeline. For instance, on the erosion equation side, despite of utilizing a large number of physical properties in existing model and yet there is some erosion phenomenon still remained unknown [9]. One of the most important challenges is the effect of particle’s morphology. Sizes, shapes and composition of sand particles are the common studied subjects in literature. Effects of particle size and shape on erosion of materials as well as transition between brittle to ductile properties of the target material require further investigation. Lastly, mechanism of how erosion rate being different for multi-phase flow regimes and the effect of fluid viscosity on erosion rate are not fully understood as well. Therefore, there are still plenty of room of improvement on erosion modeling. Currently available erosion models are too conservative and mostly based on correlation method for aforementioned physical properties which affects the efficiency of oil and gas production. Developing more accurate erosion models will definitely be helpful for optimizing production and reducing risk [4]. Thus, the objective of this study is to analyze the grain shape factor of the sand particles, to study effects of flow rate, grain shape factor and sand concentration on erosion rate in pipeline. Hence, validate and evaluate developed erosion model with experimental data.

2. Simulation and numerical method

In this paper, the numerical simulation is performed for different sand particle sizes in multiphase flows (liquid and solid) to study the effect of particle size on erosion activity. The grain shape factor coefficient used in this study ranging between 0.2 and 1.0. Details of the numerical approaches are exemplified below.

2.1 Mathematical Model

In this study, the approaches taken was Lagrangian approach and k-omega turbulent model to simulate the multiphase flow (water and sand particle). In trajectory models, the Lagrangian model is usually assumed to be discrete. In this approach, the fluid phase is solved using Newtonian equations of motion to determine trajectories of individual particles. The Lagrangian method is essential to identify appropriate model to describe particle motion, using calculation particle loading and Stokes number. The particle mass loading equation expressed as follows:

$$\beta = \frac{r_p \rho_p}{r_f \rho_f}$$

(1)

where $r$ is the fraction of volume, $\rho$ refers to density ($kg/m^3$), and the subscripts $p$ and $f$ is the particle and fluid phases respectively. Based on Newton’s law of motion, the governing particle motion equation is given as:

$$m_p \frac{dv_p}{dt} = F_d + F_p + F_b + F_a$$

(2)
where \( m_p \) is mass of particle \((kg)\), \( V_p \) is local particle velocity \((m/s)\) and \( t \) denotes time \((s)\). The right hand side terms is the drag force acting on surface due to viscous effect of fluid medium, taking account on the cohesion between particle and fluid streamline.

The continuous liquid phase is investigated by Navier-Stokes solver to develop the Reynolds Averaged Navier Stokes equations, where the liquid and solid particles are spherical properties added into continuous phase flow field known as discrete phase, which are captured by discrete phase model (DPM). The water is assumed as incompressible flow, no heat exchange between water and sand particle, and the sand particles are known as diluted phase in water. The governing equations of water phase is described as:

Turbulent kinetic energy \((k)\) equation:
\[
\frac{\partial k}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho \frac{u_i}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \Gamma \frac{\partial k}{\partial x_j} \right) - \rho \epsilon + \frac{\partial}{\partial x_i} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\partial u_i}{\partial x_j} \tau_{ij}
\]

The specific dissipation rate \((\omega)\) is given by:
\[
\frac{\partial \omega}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho \frac{u_i}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \Gamma \frac{\partial \omega}{\partial x_j} \right) + \frac{\partial u_i}{\partial x_j} \frac{\partial \omega}{\partial x_j} - \frac{\partial u_i}{\partial x_j} \tau_{ij} \frac{\partial u_i}{\partial x_j}
\]

Where turbulence kinetic energy \((k(m^2/s^2))\), dynamic viscosity \( \mu (Pas)\), dynamic viscosity for \( \mu_c (Pas)\), velocities vector \( \dot{u} \) \((m/s)\), specific dissipation rate \( \omega \) \((m^2/s^3)\), and \( t \) denotes time. The \( k - \omega \) model is preferred for several reasons. For instance, it is sensitive to near-wall interactions and more accurate for free shear flows and separated flows.

### 2.2 Erosion Mechanics and Modeling Strategies

The solid particle studies are done by many researches due to the significant of the industrial requirement. Hence, the erosion equation development is advancing empirically or numerically. In the studies aforementioned, the characteristic of solid particle concentration is described via suggesting different geometries and mechanisms. The earliest proposed erosion equations is derived via solving equations of motion for particle as it cut the target surface [10]. In this research, the erosion equations and modeling approaches are reviewed to select the suitable erosion equation [4]. The erosion equations are exemplified in Table 1.

| Model         | Equation                                                                                                                                                                                                 | References |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Ahlert        | \( ER = A(BH)^{-0.59}F_s u_p f(\alpha) \) \( f(\alpha) = a\alpha^2 + ba \leq a_0 \) \( f(\alpha) = x \cos^2 \alpha \sin(w\alpha) + y \sin^2 \alpha + z \) \( \alpha > a_0 \) | [11]       |
| DNV           | \( ER = C f(\alpha) u_p^6 \) \( f(\alpha) = \sum_{i=1}^{B} (-1)^{i+1} A_i \alpha^i \)                                                                                                                                 | [12]       |
| Neilson-Gilchrist | \( ER = \frac{u_p^2 \cos^2 \alpha \sin^2 \alpha}{2\varepsilon_c} + \frac{u_p^2 \sin^2 \alpha}{2\varepsilon_D} \) \( \alpha < a_0 \) \( ER = \frac{u_p^2 \cos^2 \alpha}{2\varepsilon_c} + \frac{u_p^2 \sin^2 \alpha}{2\varepsilon_D} \) \( \alpha > a_0 \) | [13]       |
| Oka           | \( E_{90} = 81.714 (Hv)^{-0.79} \left( \frac{u_p}{u_{ref}} \right)^2 \left( \frac{D_p}{D_{ref}} \right)^{k3} \) \( g(\alpha) = (\sin \alpha)^{n1} (1 + Hv (1 - \sin \alpha))^{n2} \) | [14, 15]   |
| Zhang E/CRC   | \( ER = C(BH)^{-0.59} F_s V_p^2 F(\theta) \) \( F(\theta) = 5.40\theta - 10.11\theta^2 + 10.93\theta^3 - 6.33\theta^4 + 1.42\theta^5 \) | [16]       |
From all the models stated above, the erosion equations are normally based on various testing conditions influenced by the effect of erosion parameters. Thus, it can be deduced that the erosion equations required experimental data to validate the given constants to generate erosion equation. Currently, there is no specified erosion equation suitable for all erosion conditions. Furthermore, the values of parameters in erosion models are defined as follows:

Table 2: Parameters values of erosion models [12, 15, 17].

| Parameters | $A$ | $B$ | $w$ | $x$ | $y$ | $z$ |
|------------|-----|-----|-----|-----|-----|-----|
| $1$        | 38.4 | 22.7 | 1   | 3.147 | 0.3609 | 2.532 |
| $2$        | $A_{1}$ | $A_{242}$ | $A_{3}$ | 175.8 | $A_{5}$ | $A_{6}$ | $A_{7}$ | $A_{8}$ |
| $k_{0}$    | 9.370 | 295 | 110.864 | 4   | 170.137 | 98.398 | 31.211 | 4.170 |
| $k_{1}$    | -0.12 | 2.3 | $H(v)^{0.038}$ | 0.19 | 0.71 $H(v)^{0.14}$ | 2.4 $H(v)^{0.94}$ | 104 | 326 |

2.3 Modified erosion model

The erosion rate depends mainly on the alteration of particle shape coefficient in addition to impact velocity, impact angle and target material properties. The Zhang E/CRC erosion model improved the particle near-wall velocity and erosion prediction through two refinement via standard wall function application at near-wall particle tracking and rebounding the particle at a radius from the wall, thus avoiding nonphysical impacts [18]. These correlations have remarkable quality of results which taken into account of the complexity of the phenomenon [19]. In this study, the empirical model developed by Zhang et al. [16] is modified by varying the particle shape coefficient. The empirical equation defined is given by:

$$ ER = C(BH)^{-0.59}F_SV_p^0F(\Theta) $$

where $ER$ is erosion ratio, $C$ and $n$ are empirical constants given as $2.17 \times 10^{-7}$ and 2.41 respectively, $BH$ is Brinell hardness of wall material, $F_s$ is particle shape coefficient while 1.0 for sharp (angular), 0.53 for semi-rounded, or 0.2 for fully rounded sand particles, $V_p$ is particle impact velocity and $\Theta$ is the particle impact angle in radian. Similarly, to Oka correlation, this is a robust model that relies exclusively on the flow data and the eroded material properties.

2.4 Computational domain and boundary condition

The geometry prepared in this work is 0.033 m diameter pipeline attached with the flow limiter. The flow limiter used throughout this thesis is a valley limiter, fluted limiter and upstand limiter with 0.0265m. The geometry generated in STAR CCM+ in a quarter of the geometry from a perspective view via boolean operation on faces. According to Lanasa [20], the upstream and downstream pipe diameter is larger than the pipe size to ensure a well advanced flow in pipelines. The restriction in the pipeline component is the limiter identifying the erosion. The computational domains are discretized using polyhedral mesh grid type. The meshing strategy adopted is the parts-based meshing (PBM) where the initial surface was re-tessellated to obtain a finer triangulation for generation of high quality volume mesh. In the current study, the surface remeshed was employer to re-triangulate and optimize the surface quality for volume meshing. The polyhedral mesh type was adopted considering factors such as the desired solution accuracy and convergence rate, the computational memory available, the quality of the starting surface mesh and quality of solution. The three different limiters studied is expressed in Fig. 1.
The effect of erosion activity is investigated on the three limiter namely, upstand limiter, fluted limiter and valley limiter with the following parameters fixed at diameter of 0.033 m, fluid density of 1000 kg/m³ and injector mass flow rate of 0.02778 kg/s.

Different limiter is considered in this study. The boundary conditions (which are inlet, outlet, symmetry and walls) is assigned to region per part and boundary per part surface. The flow profiles specified at inlet sections with distributions of fluid velocity with dynamic viscosity of 8.8871*10^{-10} Pa.s, constant density 997.561 kg/m³, turbulence intensity of 0.029 and turbulence length scale of 0.0037 m. At the outlet boundaries the mean pressure is specified and remain constant to zero value. The particles exit the domain. The walls is assumed under no slip condition for fluid phase. The solid properties is specified with a density of 2650 kg/m³ and a diameter of 2.75 mm. The physics continuum for multiphase (liquid-solid) used for present study consisted of the models k − ε standard and Lagrangian phase. Lagrangian multiphase model is the solid material while the continuum is defined as liquid material. In this model, the liquid phase properties are defined and the parameters that can be altered is inlet velocity. Moreover, the segregated model is selected to ensure the equations of fluid flow is solved separately via finite volume method. The quasi steady state is preferable as it has digitize into small element. The proposed workflow for STAR CCM+ is described in Fig. 2.

2.5 Grain Shape Factor of sand particle
The photogrammetry method adopted have to ability to produce photo real texturing, lower cost when compared to the equipment required when using other methodologies, and its portability.

The research was completed using Autodesk’s Recap to create three dimensional point clouds to visualize the model with high accuracy and efficiency. It is also compatible with AutoCAD, Revit, Infrarworsk, Civil 3D, Navisworks, Remake and more [21]. The ReCap also known as Reality Capture is used extract the
generated three dimensional meshes from ReCap for further optimization of the three dimensional models. Remake major workflows typically fall into two main categories, preparation and editing. The preparation is to capture at least forty pictures for each set of sample and uploaded to the ReCap dashboard to be processed into three dimensional model. The editing part is when the ReMake is used to clean, fix, sculpt, edit, retopo, optimize, compare, export or publish [22]. The completed three dimensional models is then sliced via Slic3r for each image to evaluate grain shape factor shown in Fig. 3.

Figure 3: Three-dimensional (3D) of solid particles.

Slic3r free software is used to convert the digital 3D model into different slice of layers to evaluate the shape transformation of the selected grain particle [23]. The proper model file generated in Autodesk ReCap is transferred into Slic3r in .stl format to slice to Scalable Vector Graphics (SVG) format. The SVG format is preferred as it can be scaled in vector format. In addition, each layer created is represented as image.

2.6 Microstructure analysis on sand particle

The sand particles grain properties is evaluated via ImageJ digital image processing program followed by MATLAB. Ten reference particles with various shapes is investigated to study the qualitative and quantitative evaluation. The ImageJ software is utilized to analyze the particle whereas the conversion of captured image into a binary is recommended [24]. With the integration of Image Processing Toolbox in MATLAB, PolyLX, which undertake the review of reference-standard algorithm, functions, and applications for image analysis, processing, visualization and algorithm development, thus the shapes of the particles is measurable [25].
Figure 4: Sliced selected particle in Slic3r.

In the current study, Fig. 4 were calibrated and converted to 8-bit grayscale images. The following approach executed in ImageJ software to obtain confident results. In ImageJ, the set measurements function are area, minimum and maximum gray value and mean gray value. The grayscale threshold is used to optimize for discrimination of particle background. The basis of cut-off value in thresholding is pixel values which will be affected by any alteration in image acquisition, thus the final binarization result depends on the enhancing on the areas of interest and fostering the binarization process to ensure the reproducibility. After thresholding, further measurements on area of interest is corrected by closing the internal holes via analyze particles [26]. The particle grains results is then key in into PolyLX MATLAB toolbox to analyze the grain particle quantitatively.

After generating the result in qualitative evaluation, the grain shape particle was further analyzed through the quantitative evaluation via MATLAB PolyLX toolbox. The PolyLX toolbox is utilized to solve the image files from ImageJ digital image processing program to analyze the textural analysis of each object in pixels [27]. The quantitative textural analysis depend on detailed and precise description of grain sizes, grain shapes, grain boundaries as well as preferred orientations of grain and grain boundaries. The selected particle shape parameters used in MATLAB toolbox are perimeter, area, length of the longest axis and length of the shortest axis which is stated in Table 3.

### Table 3: Parameters averaged values results of the selected particles.

| Particles (Fig. 3) | Length (Pixel) | Width (Pixel) | Area (Pixel) | Perimeter (Pixel) |
|--------------------|----------------|---------------|--------------|-------------------|
| Set 1              | 1564.837       | 774.32666     | 876117.79    | 5309.1429         |
| Set 2              | 923.40156      | 530.21394     | 327322.76    | 3054.2927         |
| Set 3              | 845.0879       | 680.97733     | 376549.74    | 3206.5807         |
| Set 4              | 1462.9529      | 563.70606     | 495456.38    | 4406.6667         |
| Set 5              | 1310.0961      | 844.46465     | 624014.41    | 4398              |
| Set 6              | 967.30292      | 496.43234     | 370839.24    | 3360.7059         |
| Set 7              | 1095.9541      | 825.12551     | 655308.09    | 3934.875          |
The mathematical formulation of grain shape factor properties was examined via the PolyLX toolbox grain shape factor parameters defined as Eq. (7):

\[
GSF = \left(\frac{L}{W}\right)^{0.318} \cdot \frac{P}{\sqrt{A}}
\]

whereas \( W \) represents the width in pixel, \( P \) is the perimeter in pixel, \( A \) is the grain area in pixel and \( L \) is length in pixel. Nevertheless, the grain shape factor values obtained is hard to quantify the grain shape factor of sand as the variance between the values is large. In order propose the equation, the calculated values should be normalized to the range of 0.2 to 1.0 by using Eq. (8). The min-max normalization method is adopted to scrutinize the normalized grain shape factor in the range desired [28].

\[
\text{Normalize Shape Factor} = 1 + \frac{(x-2.46279)(1-0.2)}{4.4072743-2.46279}
\]

Table 4: Normalization of grain shape factor.

| Particles (Fig. 3) | Average Grain Shape Factor | Normalized GSF |
|-------------------|-----------------------------|----------------|
| Set 9             | 2.441528788                 | 0.2            |
| Set 3             | 2.954148387                 | 0.402626939    |
| Set 10            | 3.020467347                 | 0.429975628    |
| Set 8             | 3.7595                      | 0.499070596    |
| Set 5             | 3.399502381                 | 0.586282534    |
| Set 7             | 2.89341875                  | 0.700929404    |
| Set 6             | 3.688241176                 | 0.705352972    |
| Set 1             | 3.7892                      | 0.746986488    |
| Set 2             | 3.907587805                 | 0.795807388    |
| Set 4             | 4.402742857                 | 1              |

Through the application of regression evaluation in the data analysis built in Microsoft Excel (Appendix A), a grain shape factor equation is generated according to the normalized shape factor in Table 4.

New Shape Factor = - 0.39657086 \( \left(\frac{L}{W}\right) \) - 0.1225171 \( \left(\frac{P}{\sqrt{A}}\right) \) + 1.93211497

The following particle shape distribution are tabulated into respective modified grain shape factor value shown in Fig. 5. Although in Zhang E/CRC erosion model, the assumption made for particle shape coefficient was a constant of 0.2 for fully rounded sand particles, the existence of various particle shape was found. Thus, the shapes of sand particles is analyzed via implementing the grain shape factor analysis. The grain shape factor analysis is completed through the MATLAB software via the iteration of the particle grain shape factor illustrated in Appendix B. The distribution of particle shape is examined and categorized in Table 5. Therefore, there is 75% of high sphericity of the sand particles in set 9 whereas 25% in set 10 were identified to be slightly higher in terms of roundness and angularity that contribute to the erosion rate of 0.58 g/hr.
Table 5: Particle shape distribution for shape factor of 0.265.

| Grain Shape Factor | Particles fluid distribution (%) |
|--------------------|----------------------------------|
| Set 4              | 1.00                             | 0                                |
| Set 2              | 0.82                             | 0                                |
| Set 1              | 0.80                             | 0                                |
| Set 6              | 0.77                             | 0                                |
| Set 7              | 0.61                             | 0                                |
| Set 5              | 0.50                             | 0                                |
| Set 8              | 0.49                             | 0                                |
| Set 10             | 0.45                             | 25                               |
| Set 3              | 0.40                             | 0                                |
| Set 9              | 0.20                             | 75                               |

Figure 5: The modified grain shape factor values on the ten sets of sand particles.
3. **Results and discussion**

3.1 **Minimization of erosion rate based on response surface methodology**

The application of the statistical analysis tool utilized is the design of experiment (DOE) and response surface methodology (RSM). The basic fundamentals of DOE composed of one or a series of data where the input parameters are modified to monitor the difference in the result output. The models is classified as theory and empirical models, which the models are following the statistical and machine learning method. Response surface methodology combines experimental methods and mathematical statistics, continuously testing the specified points until the relationship between parameters is solved. Also, response surface methodology explains the response tool and future values via the statistical evaluation of regression coefficient from the result [29]. Moreover, the second-order polynomials is examined, to evaluate the response value and defined effect size. The general function of RSM is expressed as:

\[
y^k = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum \sum_{i<j} \beta_{ij} x_i x_j + \sum \sum \beta_{ii} x_i^2 + \varepsilon
\]

(10)

where \(y^k\) is response purpose, \(\lambda\) is Box-Cox power transformation value, \(\beta_0\) is constant of real regression, \(\beta_i, \beta_{ij}\) and \(\beta_{ii}\) are main regression coefficients values, interaction and quadratic terms, \(x_i\) are the \(i\)th function independent variables and \(\varepsilon\) is the random error.

3.2 **Effect of particle properties and contact parameters on erosion process**

In this study, the parameters influencing erosion in pipeline with different geometry limiter is studied. The comparison between the fluted limiter, valley limiter and upstand limiter under different conditions is simulated for 15 runs and evaluated to ensure consistency analysis of result [30]. The effect of erosion activity is evaluated via the statistical analysis of fluid flow rate ranging from 25 litres/s till 50 litres/s. The effect of mass flow rate is illustrated in Fig. 6.

![Figure 6: Effect of flow rate influencing erosion activity.](attachment:figure6.png)

According to Fig. 6, it is shown that the flow rate is directly proportional to the erosion activity. The flow rate is influenced by the particle kinetic energy, hence the kinetic energy will increase as the eroded target surface area increases. This indicated that the material removal of the target surface is caused by the higher momentum of particles. Moreover, the relationship between flow rate and erosion activity can be proven using the exponential function where the power exponent is known to be equal to 2 [30].
The Fig. 7 shown the effect of grain shape factor influencing the erosion activity. The linear correlation between erosion activity and shape factor is applied to the three limiter simulated. Hence, the higher the angularity of the grain, the greater the erosion activity. The shape factor 0.2 pointed out that it is a rounded grain whereas 0.9 shown that it is an angular grain. This is due to the higher angularity grain have a more shaper edge compared to the rounded grain. Bukhaiti et al. [31] stated that the higher the angularity of grains, the sharper the edge of the angular grain, as a result the greater the eroded target surface. As the point pressure caused by the sharpness of the angular grain has reached a certain point, it will create scars, thus it contributes in the removing of surface material.

![Figure 7: Effect of shape factor influencing erosion activity.](image)

From the Fig. 8, it evaluated effect of sand concentration influencing the erosion activity. The sand concentration was set from 0.5 % to 1.0 % by weight. The erosion activity is linearly proportional to sand concentration. This relationship of the effect of sand concentration and erosion activity can be interpreted as the amount of sand particles in fluid. When the amount of sand concentration is significant, the greater the amount of solid particles collides at the target surface, hence greater rebounding action and wearing of the target surface. The results are qualitatively similar to those research published by Peng and Cao [11].
3.3 Validation of STAR CCM+ model

To demonstrate the CFD methodology, the validation case by Wallace [32] is presented in Table 6 to validate the simulation results obtained. The three different limiter in STAR CCM+ is simulated to evaluate the erosion activity of each case under the same parameters to provide a good validation case.

Table 6: Erosion experiment results [32]

| No | Description          | Time (hrs) | Mass Before (g) | Mass After (g) | Sand Conc. (%) | Mass loss (g) | Erosion rate (g/hr) | Flow rate (litres/s) | Cv Start | Cv End |
|----|----------------------|------------|-----------------|----------------|----------------|---------------|---------------------|---------------------|----------|--------|
| 1  | US, 4130            | 14         | 688.98          | 669.09         | 0.53           | 19.89         | 1.42                | 28.14               | 11.8     | 13.5   |
| 2  | US, Duplex          | 15         | 688.37          | 673.66         | 0.39           | 14.71         | 0.98                | 28.49               | 11.7     | 13.5   |
| 3  | Fluted, 4130        | 14         | 690.30          | 681.15         | 0.44           | 9.15          | 0.65                | 29.34               | 12.6     | 14.4   |
| 4  | Valley, 4130        | 14         | 838.93          | 830.77         | 0.39           | 8.16          | 0.58                | 28.57               | 12.9     | 14.7   |

The simulated data obtain is evaluated through the calculation percentage of error shown in Table 7. It can be seen that fluted and upstand has an error percentage greater than 5%, due to the different in geometry dimension constructed as insufficient information provided on the dimensions of limiter. In addition, the material of limiter studied is AISI 4130, which composed of hardness 240.9 Hv, density of 7790 kg/m³ and surface roughness 0.28μm [32].

Furthermore, the shape factor is evaluated where Zhang et al. [33] set the grain shape factor as a constant value of 0.2. The difference between simulated results and experiment data was overcome via changing the shape factor in erosion equation until it is an acceptable range close to the experimental data. Therefore, shape factor required is 0.265 and thus, the shape of sand particles varies in angularity and roundness. Consequently, the effect of grain shape factor is significant in influencing erosion activity and should be taken into consideration for further investigation.
Table 7: Comparison between experiment and simulation erosion activity.

| Limiter | Flow Rate (l/s) | Shape Factor | Sand Conc. (%) | Erosion rate (g/hr) |
|---------|----------------|--------------|----------------|---------------------|
| Upstand | Experiment     | 28.14        | -              | 0.53                | 1.42                |
|         | Simulation     | 28.14        | 0.265          | 0.53                | 1.573               |
| Fluted  | Experiment     | 29.34        | -              | 0.44                | 0.65                |
|         | Simulation     | 29.34        | 0.265          | 0.44                | 0.769               |
| Valley  | Experiment     | 28.57        | -              | 0.39                | 0.580               |
|         | Simulation     | 28.57        | 0.265          | 0.39                | 0.580               |

3.4 Formulation of new erosion

The significant of the effects of mass flow rate, shape factor and sand concentration was evaluated via analysis of variance (ANOVA) with the combination of Fisher’s statistical test. The ANOVA method utilized is to interpret the importance of the respective variable to the erosion rate, and it examine based on sum of squares and Percentage of contributions (PC) for individual values. By assuming the coupling effects of the input parameters are infinitesimal, the output response can be accurately predicted via low-dimensional functions, namely ANOVA components. Table 8 are the simulated results of a number of 20 simulation run completed. In this research, the simulation runs done is to evaluate the effects of the variables on the erosion activity. The results acquired is then analyzed via the regression analysis function in the Design Expert Software.

Table 9 reported the results of ANOVA analysis to investigate the effect of erosion activity. The model F value is monitored, where a higher F-value implies that the model is significant. Moreover, another value to identify the importance of model is through analyzing the p-value which have to be less than 0.005. Therefore, the selected model is based on the criteria mentioned. The model selected is reflected in the equation for each limiter respectively.

In order to identify the greatest effect on erosion activity, the F-value was evaluated. The greater the F value, the greater the effect on the respective model. Accordingly, the greatest to smallest F value for upstand limiter is flow rate (927.54), shape factor (865.10) and sand concentration (1.14) consecutively. The following concept applies to fluted limiter and valley limiter. This means that the influence of flow rate on erosion activity is remarkably larger compared to shape factor and sand concentration, considering that flow rate has a great impact of energy colliding onto the target surface when flow rate increases. Hence, as the flow rate increases, the larger the F value, as F value depends on the effect of flow rate whereas the effect of shape factor and sand concentration is infinitesimal. The proposed model for the erosion model is defined as shown in Eq. (11), Eq. (12) and Eq. (13):

\[
E_{\text{upstand}}(g/hr) = 33.76 + 27.14A + 26.21B + 17.29AB
\]  
(11)

\[
E_{\text{fluted}}(g/hr) = 31.07 + 24.69A + 23.8B + 15.27AB + 0.49AC
\]  
(12)

\[
E_{\text{valley}}(g/hr) = 11.33 + 9.04A + 8.56B + 6.0014AB + 2.00A^2
\]  
(13)

The model validation is performed to recognize the good agreement of data acquired by predicting the response value and compared with the simulation result. The correlation coefficient, \( R^2 \) value was 0.99953 which is an acceptable value to proceed to predict the model response and parity plot. The graph of predicted
against actual is illustrated in Fig. 9 to show its good agreement of data between erosion activity from the equations and the actual erosion activity. Fig. 10 addressed the three-dimensional plot and Fig. 11 demonstrated the desirability function established through the consideration of the key parameters of flow rate, shape factor and sand concentration.

Table 8: The simulated results and the response of each limiter.

| Run | Variables | Response |
|-----|-----------|----------|
|     | A: Flow rate (litres/s) | B: Shape Factor | C: Sand concentration (%) | Upstand Erosion rate (g/hr) | Fluted Erosion rate (g/hr) | Valley Erosion rate (g/hr) |
| 1 | 25 | 0.6 | 0.75 | 12.52 | 10.63 | 4.29 |
| 2 | 37.5 | 1 | 0.75 | 63.06 | 64.43 | 18.86 |
| 3 | 50 | 0.2 | 1 | 21.75 | 25.48 | 7.49 |
| 4 | 37.5 | 0.6 | 0.75 | 31.55 | 28.41 | 11.29 |
| 5 | 37.5 | 0.6 | 0.75 | 31.98 | 31.47 | 11.29 |
| 6 | 50 | 1 | 1 | 107.76 | 97.63 | 36.99 |
| 7 | 50 | 0.6 | 0.75 | 69.69 | 61.71 | 22.41 |
| 8 | 25 | 1 | 1 | 24.12 | 19.28 | 7.05 |
| 9 | 37.5 | 0.6 | 0.5 | 39.70 | 30.00 | 11.23 |
| 10 | 37.5 | 0.2 | 0.75 | 10.86 | 11.49 | 3.77 |
| 11 | 37.5 | 0.6 | 0.75 | 30.35 | 29.68 | 11.36 |
| 12 | 25 | 0.2 | 0.5 | 4.08 | 3.64 | 1.41 |
| 13 | 50 | 1 | 0.5 | 113.03 | 100.40 | 37.27 |
| 14 | 37.5 | 0.6 | 0.75 | 32.03 | 30.84 | 11.36 |
| 15 | 37.5 | 0.6 | 0.75 | 32.05 | 30.22 | 11.48 |
| 16 | 37.5 | 0.6 | 1 | 34.27 | 29.91 | 11.39 |
| 17 | 25 | 0.2 | 1 | 4.61 | 3.96 | 1.41 |
| 18 | 25 | 1 | 0.5 | 20.34 | 19.77 | 7.04 |
| 19 | 50 | 0.2 | 0.5 | 24.87 | 18.97 | 7.48 |
| 20 | 37.5 | 0.6 | 0.75 | 35.50 | 28.70 | 11.21 |

Table 9: Analysis of variance (ANOVA) (a) Upstand (b) Fluted (c) Valley.

| Source | Sum of Squares | df | Mean Square | F Value | p-value | Prob > F |
|--------|----------------|----|-------------|---------|---------|----------|
| Model  | 16857.91 | 9 | 1873.10 | 235.82 | < 0.0001 |
| A      | 7367.23 | 1 | 7367.23 | 927.54 | < 0.0001 |
| B      | 6871.31 | 1 | 6871.31 | 865.10 | < 0.0001 |
| C      | 9.04 | 1 | 9.04 | 1.14 | 0.3112 |
| AB     | 2394.03 | 1 | 2394.03 | 301.41 | < 0.0001 |
| AC     | 20.19 | 1 | 20.19 | 2.54 | 0.1419 |
| BC     | 1.51E-01 | 1 | 0.15 | 0.02 | 0.8932 |
| A^2    | 70.07 | 1 | 70.07 | 8.82 | 0.0140 |
| B^2    | 2.22 | 1 | 2.22 | 2.80E-01 | 0.6083 |
| C^2    | 2.35 | 1 | 2.35 | 2.96E-01 | 0.5982 |
### (b) Fluted limiter

| Source   | Sum of Squares | df | Mean Square | F Value | p-value |
|----------|----------------|----|-------------|---------|---------|
| Model    | 13821.42       | 9  | 1535.71     | 234.93  | < 0.0001|
| A        | 6096.08        | 1  | 6096.08     | 932.57  | < 0.0001|
| B        | 5662.51        | 1  | 5662.51     | 866.24  | < 0.0001|
| C        | 1.22           | 1  | 1.22        | 0.19    | 0.68    |
| AB       | 1864.74        | 1  | 1864.74     | 285.26  | < 0.0001|
| AC       | 1.91           | 1  | 1.91        | 0.29    | 0.60    |
| BC       | 12.74          | 1  | 12.74       | 1.95    | 0.19    |
| A^2      | 30.21          | 1  | 30.21       | 4.62    | 0.06    |
| B^2      | 71.68          | 1  | 71.68       | 10.97   | 0.01    |
| C^2      | 23.21          | 1  | 23.21       | 3.55    | 0.09    |
| Residual | 65.37          | 10 | 6.54        |         |         |
| Lack of Fit | 58.23     | 5  | 11.65       | 8.16    | 0.02    |
| Pure Error | 7.14        | 5  | 1.43        |         |         |
| Cor Total| 13886.79       | 19 |             |         |         |

### (c) Valley limiter

| Source   | Sum of Squares | df | Mean Square | F Value | p-value |
|----------|----------------|----|-------------|---------|---------|
| Model    | 1858.4         | 9  | 206.5       | 772.4   | < 0.0001|
| A        | 817.7          | 1  | 817.7       | 3058.9  | < 0.0001|
| B        | 733.3          | 1  | 733.3       | 2743.1  | < 0.0001|
| C        | 9.02E-04       | 1  | 9.02E-04    | 3.38E-03| 0.9548  |
| AB       | 288.1          | 1  | 288.1       | 1077.9  | < 0.0001|
| AC       | 9.79E-03       | 1  | 9.79E-03    | 3.66E-02| 0.8521  |
| BC       | 9.04E-03       | 1  | 9.04E-03    | 3.38E-02| 0.8578  |
| A^2      | 11.1           | 1  | 11.1        | 41.4    | < 0.0001|
| B^2      | 2.71E-03       | 1  | 2.71E-03    | 1.02E-02| 0.9217  |
| C^2      | 4.89E-03       | 1  | 4.89E-03    | 1.83E-02| 0.8951  |
| Residual | 2.7            | 10 | 2.67E-01    |         |         |
| Lack of Fit | 2.6         | 5  | 5.26E-01    | 62.1    | 0.0002  |
| Pure Error | 4.24E-02    | 5  | 8.48E-03    |         |         |
| Cor Total| 1861.1         | 19 |             |         |         |
Figure 9: Parity plot of the predicted against actual simulation erosion activity (a) Upstand (b) Fluted (c) Valley.

Figure 10: Three dimensional plot erosion activity (a) Upstand; (b) Fluted; (c) Valley.
Numerical optimization introduced remarkable insights through the evaluation of the optimum case to minimize the solid particles erosion activity in pipeline. The desirability function utilized the regression analysis approach in the Design Expert Software to analyze the ideal case through filtering the variables which comply with the constraints fixed for the parameters chosen. The desirability function is commonly used in the numerical optimization routine where it range from 0 (not acceptable) to 1 (ideal) based on the desired goal of each response and the priorities set by the user. This function is expressed in the Myers and Montgomery response surface methodology (RSM) text [34].

In the current work, the ideal case was to maximize the flow rate and minimize the erosion activity. Table 10 expressed the solutions provided by the Design Expert numerical optimization results following the criteria mentioned.

The Table 10 parameters are FR is flow rate in l/s, SF is shape factor, SC is sand concentration in %, ER is erosion rate g/hr and D is desirability. The highest desirability for each limiter for each case is selected, where it is shown in Table 15 below. Moreover, to validate the results obtained from Design Expert the following variables set is simulated to compare both results between numerical optimization from Design Expert and the simulation STAR-CCM+. The simulated result for each limiter is tabulated in Table 11 respectively.

Figure 11: Contour graph of erosion activity (a) Upstand (b) Fluted (c) Valley.
Table 10: Optimum case by Design Expert of different limiter with ideal conditions.

| No. | FR (l/s) | SF | SC. (%) | ER (g/hr) | D | No. | FR (l/s) | SF | SC. (%) | ER (g/hr) | D | No. | FR (l/s) | SF | SC. (%) | ER (g/hr) | D |
|-----|----------|----|---------|-----------|----|-----|----------|----|---------|-----------|----|-----|----------|----|---------|-----------|----|
| 1   | 50       | 0.2| 1       | 21.6      | 0.916| 1   | 50       | 0.2| 0.5     | 20.1   | 0.911| 1   | 50       | 0.2| 1       | 7.74   | 0.908|
| 2   | 50       | 0.2| 0.99    | 21.6      | 0.916| 2   | 49.88   | 0.2| 0.5     | 20.0   | 0.91 | 2   | 50       | 0.2| 0.96    | 7.75   | 0.907|
| 3   | 50       | 0.2| 0.99    | 21.6      | 0.916| 3   | 50.0    | 0.21| 0.5     | 20.6   | 0.908| 3   | 50       | 0.2| 0.95    | 7.75   | 0.907|
| 4   | 50       | 0.2| 0.98    | 21.6      | 0.916| 4   | 50      | 0.21| 0.5     | 20.8   | 0.907| 4   | 50       | 0.2| 0.95    | 7.76   | 0.907|
| 5   | 50       | 0.2| 0.98    | 21.7      | 0.916| 5   | 49.95   | 0.22| 0.5     | 21.4   | 0.903| 5   | 50       | 0.2| 0.5     | 7.76   | 0.907|
| 6   | 50       | 0.2| 0.97    | 21.7      | 0.916| 6   | 49.99   | 0.22| 0.5     | 22.0   | 0.9  | 6   | 50       | 0.2| 0.51    | 7.76   | 0.907|
| 7   | 50       | 0.2| 0.96    | 21.8      | 0.915| 7   | 50      | 0.2  | 0.59    | 22.5   | 0.897| 7   | 50       | 0.2| 0.92    | 7.76   | 0.907|
| 8   | 50       | 0.2| 0.94    | 21.8      | 0.915| 8   | 50      | 0.2  | 0.59    | 22.6   | 0.897| 8   | 50       | 0.2| 0.53    | 7.77   | 0.907|
| 9   | 50       | 0.2| 0.94    | 21.9      | 0.915| 9   | 50      | 0.2  | 0.59    | 22.7   | 0.896| 9   | 50       | 0.2| 0.91    | 7.77   | 0.907|
| 10  | 50       | 0.2| 0.93    | 21.9      | 0.915| 10  | 50      | 0.2  | 0.6     | 22.7   | 0.896| 10  | 50       | 0.2| 0.53    | 7.77   | 0.907|
| 11  | 50       | 0.2| 0.92    | 21.9      | 0.914| 11  | 50      | 0.2  | 0.6     | 22.9   | 0.895| 11  | 50       | 0.2| 0.89    | 7.77   | 0.907|
| 12  | 50       | 0.2| 0.92    | 21.9      | 0.914| 12  | 50      | 0.2  | 0.63    | 23.5   | 0.892| 12  | 50       | 0.2| 0.89    | 7.77   | 0.907|
| 13  | 50       | 0.2| 0.92    | 22.0      | 0.914| 13  | 50.0    | 0.2  | 1       | 24.3   | 0.887| 13  | 50       | 0.2| 0.55    | 7.77   | 0.907|
| 14  | 50       | 0.2| 0.91    | 22.0      | 0.914| 14  | 50      | 0.2  | 1       | 24.6   | 0.885| 14  | 50       | 0.2| 0.57    | 7.78   | 0.907|
| 15  | 49.88    | 0.2| 1       | 21.6      | 0.914| 15  | 50      | 0.2  | 0.97    | 24.7   | 0.884| 15  | 50       | 0.2| 0.58    | 7.78   | 0.907|
| 16  | 50       | 0.21| 1       | 22.4      | 0.912| 16  | 50      | 0.2  | 0.71    | 24.7   | 0.884| 16  | 50       | 0.2| 0.85    | 7.78   | 0.907|
| 17  | 50       | 0.2| 0.84    | 22.5      | 0.912| 17  | 50      | 0.2  | 0.95    | 25.0   | 0.883| 17  | 50       | 0.2| 0.59    | 7.78   | 0.907|
| 18  | 50       | 0.2| 0.84    | 22.5      | 0.911| 18  | 50      | 0.2  | 0.94    | 25.0   | 0.883| 18  | 50       | 0.2| 0.59    | 7.78   | 0.907|
| 19  | 50       | 0.2| 0.82    | 22.7      | 0.911| 19  | 50      | 0.2  | 0.92    | 25.2   | 0.882| 19  | 50       | 0.2| 0.83    | 7.78   | 0.907|
| 20  | 50       | 0.2| 0.82    | 22.7      | 0.911| 20  | 50      | 0.2  | 0.92    | 25.2   | 0.881| 20  | 50       | 0.2| 0.61    | 7.78   | 0.907|
Table 11: Model validation simulation data and Design Expert optimum condition.

| Limiter | Flow Rate (l/s) | Shape Factor | Sand Conc. (%) | Erosion rate (g/hr) | Percentage of Error |
|---------|----------------|--------------|----------------|--------------------|---------------------|
| Upstand | Simulation     | 50           | 0.2            | 1                  | 21.595              |
|         | DOE            | 50           | 0.2            | 1                  | 21.748              |
|         |                |              |                |                    | 0.703 %             |
| Fluted  | Simulation     | 50           | 0.2            | 0.5                | 19.633              |
|         | DOE            | 50           | 0.2            | 0.5                | 19.768              |
|         |                |              |                |                    | 0.681 %             |
| Valley  | Simulation     | 50           | 0.2            | 1                  | 7.483               |
|         | DOE            | 50           | 0.2            | 1                  | 7.493               |
|         |                |              |                |                    | 0.128 %             |

The calculation percentage of error is examined to validate the optimized model. Therefore, the error is less than less than 0.8% thus it is reliable for optimization of erosion rate. This proven the statistical analysis is reliable for determination of the optimized erosion activity.

4. Conclusions
The outcome of this project is a numerical approach for the simulation on effect of two-phase flow in pipelines, for fluted limiter, upstand limiter and valley limiter. The proposed E/CRC Modified erosion model is utilized to simulate the erosion activity for 11mm diameter for the limiter with length of 0.033 m pipeline. STAR CCM+ software was used to simulate the specified conditions via different limiter’s constructed through 3D-CAD. Based on the model, the erosion activity was simulated according to the experiment data in terms of flow rate, grain shape factor and sand concentration, and the percentage error is lower than 16% and this could be explained as the simulated limiter dimension is not constructed based on the actual experiment limiter dimension, thus discrepancy of values of erosion activity occurs Wallace [32] and further investigation is suggested. The shape factor from Zhang E/CRC erosion model was altered until it matches with the experimental erosion rate from Wallace’s research, thus the shape factor 0.265 was reported.

Apart from that, the shape distribution of solid particle in fluid flow was investigated through the demonstration of microstructure analysis of ten selected sand particles using ImageJ and MATLAB. The formulation of new grain shape factor equation is generated for the selection of the suitable shape factor of solid particles in evaluating the erosion rate. The newly generated grain shape factor equation demonstrated that shape factor particles are defined as 75% of 0.20 shape factor and the remaining 25% of 0.45 shape factor present in fluid. These particles are tabulated through consideration of roundness and sphericity to conclude an overall grain shape factor of 0.265 which corresponds to the erosion activity of the limiter’s respectively.

One of the main scope of this project is to develop, analyze and validate the different limiters affecting the erosion activity on the targeted surface. Results from CFD simulations were generally used to compare with the experimental results to study the erosion activity, where the velocity parameter is considered. Moreover, the numerical optimization approach is taken to analyze the parameters are through the engineering-statistical tools, DOE and RSM. The ANOVA technique is implemented to evaluate the importance of each factor and the response rate. The parameters are scrutinized to investigate the effects of erosion activity. In order to study the effect of mass flow rate, shape factor and sand concentration on erosion activity, the numerical method was applied. The statistical analysis conducted on each factor to analyze the effect of erosion activity, hence it can be concluded that the relationship between the parameters is presented (fluid flow rate > shape factor > sand concentration). The optimum condition to minimize...
erosion activity in the limiter is under the settings of the following sequence flow rate, shape factor and sand concentration presented as 50 litres/s, 0.20 and 1.0 % respectively. The numerical results are promising and encouraging for future research areas. Therefore, some areas for further study are the prediction of piping maintenance for coat surface or sample collection of changing pipe to evaluate sand particle erosion rate can be done at a certain period. Furthermore, additional storage tank to settle down the solid particle to produce low grain shape factor and low sand concentration for pipe transportation.

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