Numerical Study the Effect of Undulation to Mitigate Erosion Elbow

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Abstract: Wear is a problem that is often encountered in the production process. It can cause erosion in the production section of the pipe. Wear and tear can cause erosion resulting in leakage in the pipe, so it is necessary to predict erosion on the elbow pipe. In this study, CFD modeling on ANSYS 19.1 application was used to predict erosion in air flow with variations in undulation and combined with a twist configuration can reduce erosion in the elbow pipe. This is to determine whether the modeling with a certain number of undulation and combined with a twist configuration can reduce erosion in the elbow pipe. Changes in flow greatly affect the rate of erosion because they can affect the interaction of particles with the wall and the speed of impact. The final result of this research is that the pipe with the 3-undulation variation reduces erosion by 38%, while the pipe with the 5-undulation variation reduces erosion by 22% compared to the planned pipe.

1 INTRODUCTION

Wear is a problem that is often encountered in the production process. This is because it can cause erosion in the production section of the pipe. The process is repeated over and over again, resulting in the pipe will often experience friction and pressure with coal particles. Coal particles gain momentum from the fluid passing through the flow path and impacting the walls, resulting in erosion (Yudhatama, Purbawanto, and Jatimurti 2018). Pneumatic particles that move generally can trigger the erosion process and impact the wall. The impact produces particle interactions (Duarte and de Souza 2017). In addition, the mixture of gases and sand particles passing through the pipe combined with the velocity and nature of the fluid creates a risk for different equipment. Therefore, it is expected to be able to predict erosion accurately (Strømme 2015).

A simulation was carried out in this study to determine the erosion rate at the pulverizer outlet pipe using 4-undulation and 8-undulation variations. Undulation is a waveform in a pipe by combining similar circles and varying in several angles. This aims to determine the pipe location that may experience the earliest leakage due to coal and the best geometry to reduce erosion. Then the results of this study can then be used as a reference to prevent erosion on pipe elbows in various industries.

2 NUMERICAL METHOD

Computational Fluid Dynamics (CFD) is the art of replacing integral and partial differential equations into discrete algebraic equations, which can then be solved to obtain solutions in the form of flow values at discrete points of space and time (Anderson 1995). In the case of air fluid flow using sand, the CFD model equation is used. (Diana et al. 2020)

2.1 Flow Modelling

Flow modeling is the first step in the erosion prediction stage using CFD to solve the Navier-Stokes equation or adjust the fluid motion equation. In most circumstances, the fluid flow through the pipe is critically affected by the presence of the pipe wall. The no-slip condition between the fluid and the wall causes a change in the mean velocity field in the near wall region, where viscous damping and kinematic blocking reduce the velocity and normal fluctuations near the wall. However, a large gradient in the mean velocity causes the production of turbulent kinetic energy which consequently builds up turbulent flow towards the center of the pipe as the fluid flow approaches the core region of the pipe (Wee and Yap 2019).

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2.2 Secondary Phase Modelling

Discrete phase modeling was chosen to model the secondary phase because the volume fraction of sand in the fluid flow is below 10% (Wee and Yap 2019). The particle trajectory is calculated by integrating the particle motion under the Lagrangian frame of reference, where the drag force, pressure gradient force, and buoyancy forces are considered as follows:

$$\frac{d\overrightarrow{u_p}}{dt} = \overrightarrow{F_D} + \overrightarrow{F_P} + \overrightarrow{F_G} + \overrightarrow{F_{VM}} \tag{1}$$

Drag force $\overrightarrow{F_D}$ is the force resulting from the interaction between solid particles and a continuously moving fluid. Of all the resulting particle forces, the hydrodynamic or drag force $\overrightarrow{F_D}$ has the dominant effect on determining the trajectory of the particle. The equation $\overrightarrow{F_D}$ is given as follows:

$$\overrightarrow{F_D} = \frac{18\mu}{\rho_p {d_p}^2} \frac{C_d Re_p}{24} (\vec{u} - \overrightarrow{u_p}) \tag{2}$$

Where C_d is the drag coefficient and Re_p is the Reynold number of the particle. The values of C_d and Re_p are obtained by the following equation:

$$C_d = a_1 + \frac{a_2}{Re_p} + \frac{a_3}{{Re_p}^2} \tag{3}$$

$$Re_p = \frac{\rho d_p |\vec{u} - \overrightarrow{u_p}|}{\mu} \tag{4}$$

Where a_1, a_2 dan a_3 are constant smooth spherical particles. $\overrightarrow{F_P}$ is the pressure gradient force of the particles with the exchange of pressure between particles. The equation governing $\overrightarrow{F_P}$ is:

$$\overrightarrow{F_P} = \left(\frac{\rho}{\rho_p}\right) \nabla P \tag{5}$$

The Buoyancy Force is the force that holds the particles from the fluid, the equation that governs the Buoyancy Force is:

$$\overrightarrow{F_G} = \left(\frac{\rho_p - \rho_f}{\rho_p}\right) \vec{g} \tag{6}$$

Particle dispersion due to turbulence in the fluid phase can be corrected using the stochastic tracking model (Wee and Yap 2019).

3 PARTICLE WALL INTERACTION

For non-rotating particles, the interaction of the particles with the wall causes a loss of energy due to the inelastic impact with the wall. This causes the particle to bounce off the boundary as its momentum changes. The change in momentum is defined as the coefficient of restitution. The normal coefficient of restitution is the sum of the momentum in the direction normal to the wall that holds the particle after collision with the boundary. Similarly, the tangential coefficient of restitution is the sum of the momentum in the direction tangential to the wall holding the particle. The effects of particle behavior with walls were described in the application of the Forder Rebound Model. The Ford Rebound Model was chosen based on the type of collision used, which is sand and iron particles (Wee and Yap 2019). It is possible more stable to predict the interaction of the particles with the walls in this final project.

4 EROSION MODELLING

The equation used is a variation of the speed and impact angel performed by Oka and Yoshida. The equation uses a model based on the same material at varying speeds. In the Oka equation (Oka, Okamura, and Yoshida 2005), the erosion damage is written as:

$$E(a) = g(a) E_{90} \tag{7}$$

Where $g(a)$ is the impact angle using trigonometric functions and initial Vickers hardness (Hv). n1 and n2 are exponents obtained from eroded material hardness and other impact conditions.

$$g(a) = (sina)^{n1} \left(1 + Hv(1 - sina)\right)^{n2} \tag{8}$$

E_{90} is a representation of erosion at the normal collision angle, it is related to the impact speed, particle diameter, and the hardness of the eroded material. Then the equation is:

$$E_{90} = 81.714\, Hv^{-0.79} \left(\frac{Up}{Uref}\right)^{k2} \left(\frac{Dp}{Dref}\right)^{k3} \tag{9}$$

Up and Dp are the impact velocity and diameter, while $Uref$ and $Dref$ are references to the impact velocity and diameter as described by Oka (Oka, Okamura, and Yoshida 2005). While k2 is the exponent of eroded material hardness and property of the particle. For k3 is a parameter taken from the property of the particle. Thus, the erosion rate can be calculated with the desired wall domain with the equation:

$$Ef = \frac{1}{Af}\sum_{\pi(f)}^{0} m_{\pi}E(a) \qquad (10)$$

Where Af is the wall surface area, m_{π} is the particle flow rate and Ef is the erosion ratio.

5 CFD MODELLING

5.1 Geometry

Undulation is a waveform with settings on the number of loops configured with angle settings. In this final project, 3-undulation and 5-undulation configurations are used and make a pipe that twists along the inlet flow of the elbow pipe.

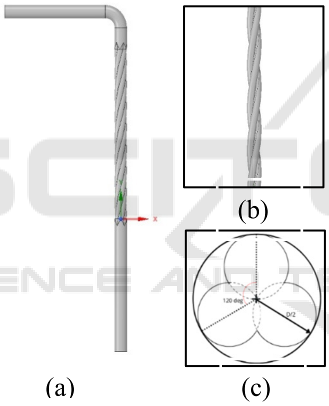


Figure 1: Pipe section scheme with 3 undulation.

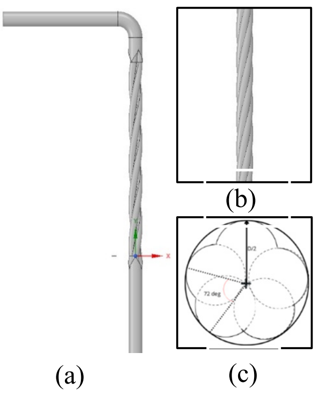


Figure 2: Pipe section scheme with 5 undulation.

Table 1: Pipe Properties.

Properties	Value	unit
Elbow pipe diameter	76.2	mm
Elbow pipe inlet length	1000	mm
Elbow pipe outlet length	600	mm
Elbow pipe radius 90º	114.3	mm

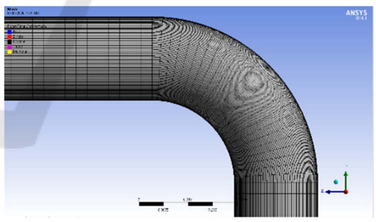
6 MESHING

Meshing is an important stage in CFD, this is because meshing divides the components to be analyzed into smaller elements. In general, the cell shape of meshing is divided into 4 shapes for 3D geometry, namely tetrahedron, pyramid, triangular prism, and hexahedron.

Table 2: Comparison of the number of cells for each variation.

Pipe Type	Number of cell	Element quality
Plan pipe	464662	0.45123
3-undulation pipe	540129	0.39183
5-undulation pipa	539532	0.52148

Meshing on the elbow will use a hexahedron cell shape. This is because it shows that the use of the hexahedron shape has a good mesh size value



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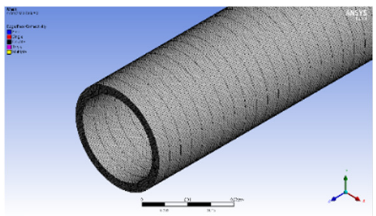


(b)

Figure 3: Pipe section scheme mesh.

7 BOUNDARY CONDITION

The boundary condition is the boundary condition of the mathematical equation and analysis is used. Boundary conditions are used as parameters to be executed by FLUENT.

Table 3: Boundary condition.

Boundary condition	Set up
Inlet	Velocity inlet DPM, discreate phase BC type : escape
Wall	Solid material : aluminium
Outlet	Pressure outlet

8 MATERIAL PROPERTIES

There are two properties used, as shown in Table 4 and Table 5. The study used air-fluid and sand injection.

Table 4: Air-Fluid Properties.

Material	Velocity (m/s)	Viscosity (Kg/ms)	Density (Kg/m^3)
Air	80	1.8×10^{-5}	1.125

Table 5: Sand Properties.

Properties	Value	Unit
Shape Factor	0.53	-
D_{min}	65	µm
D_{max}	360	µm
D_{mean}	177	µm
Spread diameter (n)	4.10	-
Density	2650	Kg/m^3

9 SET UP

Initial setup is an important stage in the simulation. This is because the setup is a process in choosing the right model for the case. In this study, the commercial program ANSYS Workbench 19.1 was used with the Fluid Flow (Fluent) package. FLUENT settings as follows:

Table 6: Set Up Fluent.

Solver	Pressure-Based Steady State Solver	
Solution Scheme	SIMPLE algorithm (Segregated)	
Spatial Discretization	Gradient	Least Squares Cell Based
	Pressure	Second Order
	Momentum	Second Order Upwind
	Specific Dissipation rate	Second Order Upwind
	Reynold Stresses	Second Order Upwind

Table 7: Set Up Fluid Properties.

Fluid	air
Thermal	-
Multiphase	-
Model Turbulent	*Realizable k-ε*
Near-wall treatment	*Scalable wall function*
Fluid viscosity	1.8 E-05 [kg/ms]
Velocity inlet	80 [m/s]
Wall condition	*No slip, smooth wall*
Gravity	9.81 [m/s^2]
Particle flow rate	0.78 [m/s]
Temperature	25^o [C]
Pressure	101325 [Pa]
Density	1.18 [kgm^{-3}]

Table 8: Set Up Sand Properties.

Injection type	*surface*
Erosion model	Oka
Drag law	*Spherical*
Distribution Diameter	*Uniform*

10 RESULT AND DISCUSSION

10.1 Mesh Independence

Mesh independence is based on the erosion ratio value in ANSYS Workbench 19.1. From all the mesh variations, the best variation will be chosen by considering the situation in the simulation. Mesh independence in this study project uses 4 variations of mesh, namely:

Table 9: Mesh independence.

Mesh	Cell number
A	78459
B	464662
C	631611
D	785452

At a fluid velocity of 80 m/s, the highest erosion rate results, namely meshing B, so that the next approach will use meshing B, but by taking into account geometric variations it is necessary to review the quality of the meshing not only in terms of the number of cells.

11 VALIDATION

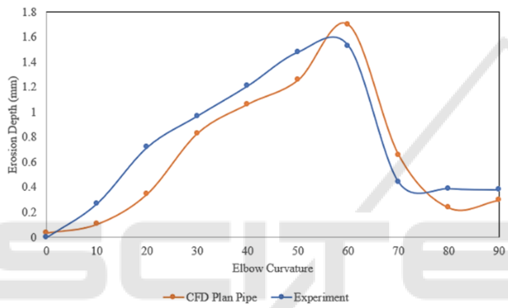


Figure 4: Comparison graph of experimental data and CFD data at a fluid velocity of 80 m/s.

Validation is an activity to prove the results obtained through the same stages and processes as the reference. Validation is done so that the results obtained are close to the desired and research gets maximum results in observation

In this study, validation was carried out by comparing the graph of the erosion rate results obtained with the erosion rate graph from the reference journal (Wee and Yap 2019).

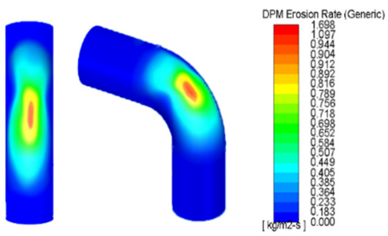
Because in the simulation there is no twisted pipe configuration, the validation is done by comparing the 90º elbow pipe with the reference. In this case, the validation error reaches 7.36%, this is possible because of the simulation situation that allows loading too much data, as well as experimental data that cannot be adjusted to conditions similar to ideal conditions.

12 THE COMPARISON OF VARIATION PIPE

In the observations, several things can affect the rate of erosion. Among others:

- Particle impact velocity
- Particle impact angle
- Properties of particles
- The target material (in this final project, stainless steel 316 is used)

Undulation is a circular shape on the elbow pipe to get a very turbulent flow result. Naturally, the particles will follow the results of the turbulent flow, the particles will spread throughout the pipe wall. With a pipe shape like this, the impact on the elbow pipe will decrease in the same point concentration. In the plan pipe the particles will focus more on the same point because there are no obstacles before turning 90



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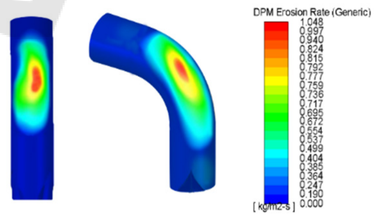

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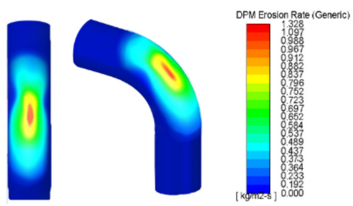

(c)

Figure 5: Contour DPM Erosion Rate (a) pipa plan, (b) 3-undulation pipe (c) 5-undulation pipe.

degrees. In this case, the things that affect the rate of erosion are caused by the roughness of the walls and the collisions between particles.

On the other hand, the variation pipe has a circular shape and is designed to limit the movement of particles. Compared to the plan pipe, the variation of the pipe makes the elbows have a low risk of erosion. This is because the wall is designed to have undulation as a limited space for particle velocity. particles with pipe walls. Experiments are the best way to accurately determine the erosion rate problem that occurs. However, to make it easier to do numerical computational studies to understand the erosion rate phenomenon that occurs in many workpieces.

Figure 5 shows the erosion phenomenon and its estimate in mm/year. Figure 5 (b) has the lowest erosion value compared to other variations. This result was obtained because the concentration of particles that hit one point was reduced and scattered at several other points. This is evidenced by the low impact velocity value resulting in a low erosion rate.

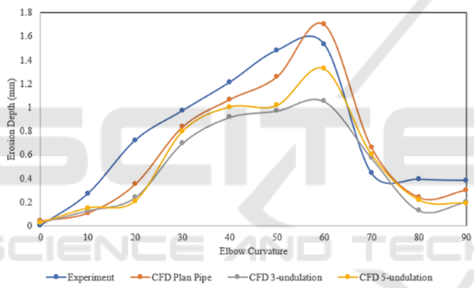

Figure 6: Graph of Erosion Rate Against Elbow Curvative at Centerline.

Figure 6 shows the graph of the erosion rate in each variation having a graphic shape that is almost the same as the planned pipe having the highest value. In the plan pipe, all particles are focused on entering the same tunnel so that they strike the same angle, while for the 3-undulation pipe and 5-undulation pipe variations, there is a special space to make the particles turbulent and spread throughout the pipe. This phenomenon causes the erosion rate value for 3-undulation and 5-undulation pipes to be lower than plan pipes. This result is almost similar to the study conducted by Duarte (Duarte and de Souza 2017) where the small amount of undulation results in a lower erosion value.

There is a comparison of the experimental test conducted by Christopher B. Solnordal (Solnordal, Wong, and Boulanger 2015) with the CFD simulation carried out. In Figure 4.3 it can be seen that the experimental test value is higher than the CFD value on the planned pipe. In this case, many things happened in the experimental test which was not ideal. When compared with computational simulation, the experimental value can be influenced by environmental conditions that can affect the simulation value.

Figure 6 shows the results of erosion at the centerline of the extrados pipe, in this case, it can be seen that the 3-undulation pipe has the lowest erosion peak value compared to the experimental, plan pipe, and 5-undulation pipe. Extrados is the outer profile of the pipe, while intrados is the inner profile of the pipe. In Figure 5 both sides (extrados and intrados) experience different erosion, on the intrados side the pipe forms a region called separated region, where separated region results in low velocity of the pipe. This causes no erosion on the intrados side of the pipe.

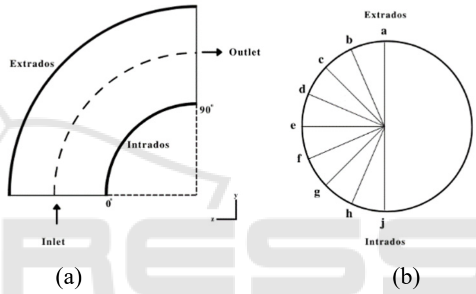

Figure 7: (a) schematic of the x-y section of the pipe (b) schematic of the profile of the x-z section of the pipe.

To get more accurate results, knowing the erosion value on the pipe profile is carried out. It aims to observe the distribution of erosion on 3-undulation and 5-undulation pipes. The profile used is an x-y cross-section with 9 points from extrados to intrados. Figure 7 shows a schematic showing the inlet point at 0° and the outlet point at 90°, as well as the x-y and x-z cross-sectional profiles on the pipe. This treatment is to make it easier to analyze the erosion relationship with the position on the pipe profile

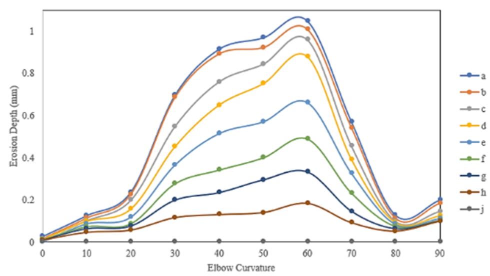

Figure 8: Graph of representation of erosion rate on 3-undulation profile.

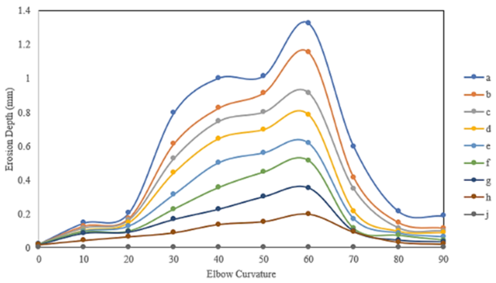

Figure 9: Graph of representation of erosion rate on 5-undulation profile.

In Figures, 8 and 9 the highest erosion rate values are at an angle of 60º. It was observed on the 3-undulation pipe that the erosion difference in the a-b profile was 0.038, the b-c profile was 0.051, the c-d profile was 0.079. Meanwhile, in the 5-undulation pipe, the erosion difference in the a-b profile is 0.169, the b-c profile is 0.240, the c-d profile is 0.127.

From this case, it is explained that the decrease in erosion value at the peak point of the 60º centerline angle (profile A) of the pipe has an impact on increasing erosion in the area around the centerline. This proves that the decrease in erosion is caused by the spread of sand particles, that the impact can be evenly distributed on each pipe profile. This can be observed directly by looking at the slope of Figures 8 and 9, wherein the 5-undulation pipe. The peak value of erosion has a far difference compared to other angles, and Figure 9 has a sharp indentation at an angle of 60º. However, the impact produced by the distributed particles does not make the erosion profiles b, c and d in 3-undulation pipes have higher yields than 5-undulation pipes. In terms of quantity, the lowest erosion rate was experienced by the 3-undulation pipe. Although the area around the center line has almost the same erosion value, it does not make the 3-undulation pipe value worse. It is proven that table 4.1 on 3-pipe undulation pipe can reduce erosion up to 38%.

The value of the erosion rate is not only caused by different geometries, but the impact velocity also affects. The provision of special space to make changes to the flow in the pipe also has an impact on the rate of erosion, with undulation, the flow in the pipe will become very turbulent (turbulent) so that it can slow down the velocity of particle impact on the pipe elbow.

In Figure 6 it can be seen that the value of the erosion rate has a significant difference at an angle of 30º – 60º. This is due to the fact that the impact velocity value is also reduced at an angle of 30º – 60º. High erosion values result in the possibility of pipe leaks occurring.

The difference in the value of the erosion rate caused by the impact velocity can also be seen from the velocity contour in Figure 10. As previously explained on the intrados side of the pipe, it forms a region called a separated region. The separated region has a low velocity so that the impact velocity becomes weaker. At certain angles on the pipe extrados, the erosion value becomes very high, such as an angle of 60º. This causes erosion, the injection of particles hitting the extrados area having more energy than increasing velocity.

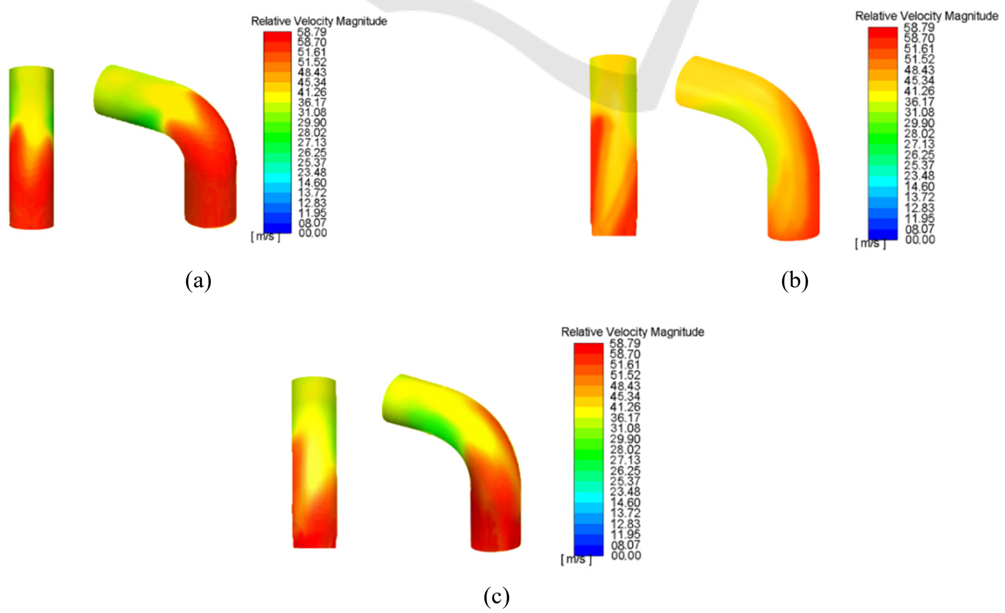

Figure 10: Contour velocity on (a) plan pipe, (b) 3-undulation pipe, (c) 5-undulation pipe.

Erosion is not only influenced by moving particles or collisions between particles, but the fluid that flows along with the particles is a determining factor for erosion. Therefore, the velocity of the elbow pipe can also be analyzed to determine the cause of erosion.

In the results of the velocity contour in Figure 10, it can be seen that the velocity contour on the pipe plan in Figure 5 (a), has the highest value. Meanwhile, 3-undulation and 5-undulation pipes have lower speeds. The impact of this phenomenon is to reduce the rate of erosion (figure 5). The velocity contour shows that the velocity value decreases from the extrados to the intrados, this is caused by a separate area on the pipe, this area is called a separated region. A separated region is an area where the lowest velocity value is on the inside of the pipe. The 5-undulation form has a value that is almost similar to the planned pipe, this can be due to the more the number of undulations the pipe wall shape will be closer to a circle or plan pipe compared to the 3-undulation form.

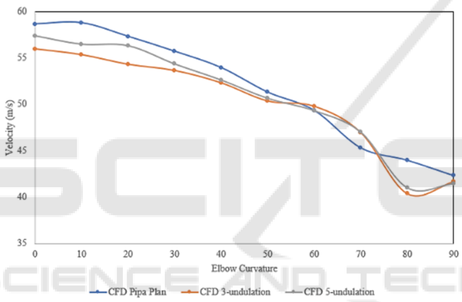

Figure 11: Graph of representation of erosion rate on 5-undulation profile.

The 5-undulation form has a value that is almost similar to the plan pipe, this can be due to the more the number of undulations the pipe wall shape will be closer to a circle or plan pipe compared to the 3-undulation form.

Table 10: Comparison of % erosion reduction in pipes with variations.

Variation	erosion value in 60^{o}	% erosion reduction
pipa plan	1.69875	-
3-undulation	1.04865	38.26
5-undulation	1.32466	22.02

Table 10 shows the results that the % erosion reduction value produced by 3-undulation pipes is higher than 5-undulation pipes. In the 3-undulation pipe, erosion can be reduced to reach 38.26%, while in the 5-undulation pipe the erosion can be reduced to 22.02% of the planned pipe. This shows that the pipe design with 3-undulation can be considered in the future as a tool to reduce the rate of erosion.

13 CONCLUSION

This research is a study of sand erosion on the elbow pipe. Gas flow is used to determine the rate of erosion at 90^{o} pipe bends. Making 3-undulation and 5-undulation designs is an effort to reduce the erosion phenomenon in pipe bends. In this study, the following results were obtained:

- Changes in flow greatly affect the rate of erosion because they can affect the interaction of particles with the wall and the velocity of impact. The highest erosion value remains on the plan pipe and the lowest erosion value on the 3-undulation pipe.
- 3-undulation pipe reduces erosion by 38.26% while 5-undulation reduces erosion by 22.02%

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