IOP Conf. Series: Materials Science and Engineering **328** (2018) 012023 doi:10.1088/1757-899X/328/1/012023

A Preliminary Experimental Investigation of Wet Fine Erosion in Two-Phase Flow

H. H. Ya[1], Haziq luthfi[1], Nguyet-tran ngo[2], Suhaimi Hassan[1], William pao[1]*
[1]Mechanical Engineering Department, Universiti Teknologi PETRONAS,
32610 Seri Iskandar, Perak DR, Malaysia
[2]Worley Parsons Pte. Ltd., 111 Somerset Road, Singapore 238146
*Corresponding Author: william.pao@utp.edu.my

Abstract. Solid particles below 62 µm is classified as fine. In oil producing operation, the most commonly used downhole sand screen can only capture solid particles of 140 µm and above. Most predictive erosion model is limited to particle size of 100 µm with single phase flow assumption because it is commonly believed that erosion due to particles below 100 µm is insignificant and typically ignored by oil and gas consultants when proposing facilities design. The objective of this paper is to investigate the impact of fines particle on mild steel plate in two-phase flow at different collision angles. A two phase flow loop was set up. The average size of fine particle was 60 µm, mixed with water with sand to water ratio at 1:65 wt/wt. The mild steel plates were oriented at three different impact angles which are -30°, 30° and 90°, with respect to the horizon. Scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), surface roughness and Vickers micro hardness techniques were used to quantify the effects of fine particle on the exposed surface.

Keywords: Two-phase flow, particle's impact, erosion, impact angle, mild steel.

1. Introduction

Solid particle erosion is one of the common problems in oil and gas industry. For many decades, it was believed that fine particles, with size below 62 µm, being very small in size; do not significantly damage the metallic flow-lines. However, the erosion studies on the microscopic scale have revealed that particles of even smaller sizes can be lethal during the production process [1]. They can escape through the most commonly used sand screens in the industry, sieve mesh 105. This made fines almost inevitable in oil and gas production. They can severely damage the installations at the location where coarse particles cannot reach in normal situations [2].

Many investigations have been conducted to develop empirical and numerical models of the solid particle erosion [2]. Upon careful study, it is found that many existing erosion correlations used in the industry has some serious drawback assumptions on single phase flow. It is also found that almost all correlations for solid particle erosion focused mainly on sand particle, which by definition is solid particles of size 62 – 2000 µm. In one of the most authoritative guidelines on sand controlled erosion for oil and gas industry, DNVGL-RP-O501 standard (2007) [3], the lower limit of the validity of model is also restricted to sand particles under single phase flow condition. The objective of this paper is to conduct a preliminary experimental investigation on the erosion caused by fine particle, i.e. solid particles of average size 60 µm; and their impact on mild steel.

The motivation is to determine if it is feasible to carry out longer term fine particle erosion research and to have a screening assessment of its impact on metallic oil and gas flow lines.

2. Literature Review

2.1. Mechanism of solid particle erosion

When a particle impacts a surface, it scars the surface. Shapes of these scars depend on many parameters including surface material, particle size, and impact angle. Researchers studied these scars to explain the mechanism of erosion and generally agree that the mechanism of erosion changes based on the ductility of the surface. [4] proposed a micro-geometry erosion model for ductile materials and suggested that erosion in ductile materials is the result of micro-cutting. When a particle impacts a surface at a low impact angle, it creates a crater. Other particle impacts make the crater larger and also pile up material around the crater. The piled up material is eventually removed by continued particle impacts. The micro-geometry model under-predicts erosion magnitude from the particles which impact the surface at higher angles compared to experimental data. [5] showed that initial erosion is lower than erosion from previously eroded surfaces and proposed a macroscopic erosion mechanism. He suggested that particles hitting the surface create shallow craters and platelet-like pieces. These platelets are easy to separate from the surface by subsequent particle impact as shown in Fig. 1. During the formation of platelets, adiabatic shear heating on the surface and work-hardening under the surface occur. The occurrence of these two processes helps platelet formation which explains the higher erosion rate for the steady-state condition compared to the initial erosion rate. Other solid particle erosion mechanisms for ductile materials are suggested by researchers and can be found in literature [6, 7, 8, 9]. Unlike the solid particle erosion mechanism for ductile materials, there is wide acceptance of the erosion mechanism for brittle material. It has been suggested that in brittle material, erosion is due to crack formation [10, 11, 12]. When a particle hits a brittle surface, it creates lateral and radial cracks. Other impacts cause these cracks to grow. These cracks divide the surface into smaller pieces which can be removed by other particles impacting the surface as shown in Fig. 2.

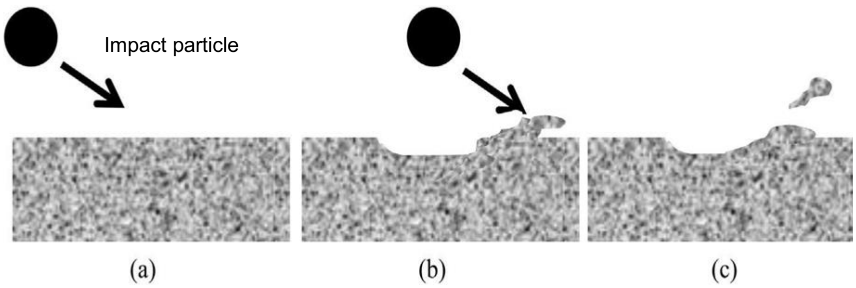


Fig. 1: Schematic of erosion mechanism in ductile material [12], (a): before the impact, (b): crater formation and piling material at one side of the crater, (c): separation of material from the surface

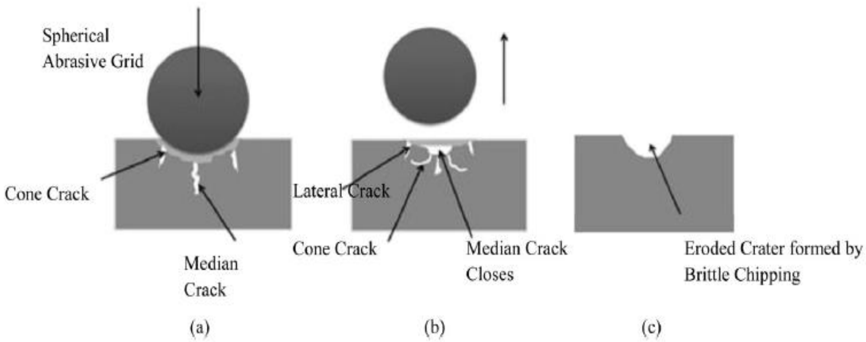


Fig. 2: Erosion mechanism by solid particle in brittle material [10, 11, 12]

2.2. Particle properties on erosion

Review from various researchers [13, 14, 15] yielded that the angularity has a great impact on erosion behaviours, whereby sharp particles are more aggressive than rounded ones. In particular, the study on erosion causing by angular solid particles has measured the influence of individual angular particles on lead and mild steel target surface [13]. [15] utilized sharp angular particles and spherical particles to investigate the effect of particles shape on erosion for steel material. They have found that angular particles imposed quadruple effect on the erosion as compared to spherical particles.

The size of particles impinged onto target surface defines the degree of erosion impact on the inner wall. The relationship between erosion rate, $\dot{E}$, and particle diameter, D_p , was revealed by Desale et al. [16] as

$$\dot{E} = f\left(D_p\right)^n \quad , \tag{1.1}$$

where n is known as the particle size factor. According to [17], the value of this 'particle size factor' varied with particle size distribution, particle velocity, fluid properties, particle-particle interaction, material properties as well as experimental conditions. At n = 1, erosion rate has linear relations with sand size. Additionally, through the erosion analysis on aluminium alloy (AA 6063) using eight different sized quartz particles in between 37.5 μm and 655 μm at two different impact angles of 30º and 90º, Desale et al. [16] summed up that at the larger size of sand particles, the higher kinetic energy, thus greater erosion wear was observed. [17] studied the relationships amongst erosion rate and flow velocity and particle sizes. Particles size of 100 μm – 10 nm were studied, in a flow regime of 5-20 m/s with different volumetric concentration of particles. They concluded that there is a threshold velocity and particles size where erosion is significant and correlate the power law relationship between average erosion rate and particles concentration, velocity and particle size. In general, the rate of erosion is found to be proportional with the ratio of hardness of particles (H_p) to hardness of target surface (H_t), defined as

$$\dot{E} \propto \left(H_p / H_t\right). \tag{1.2}$$

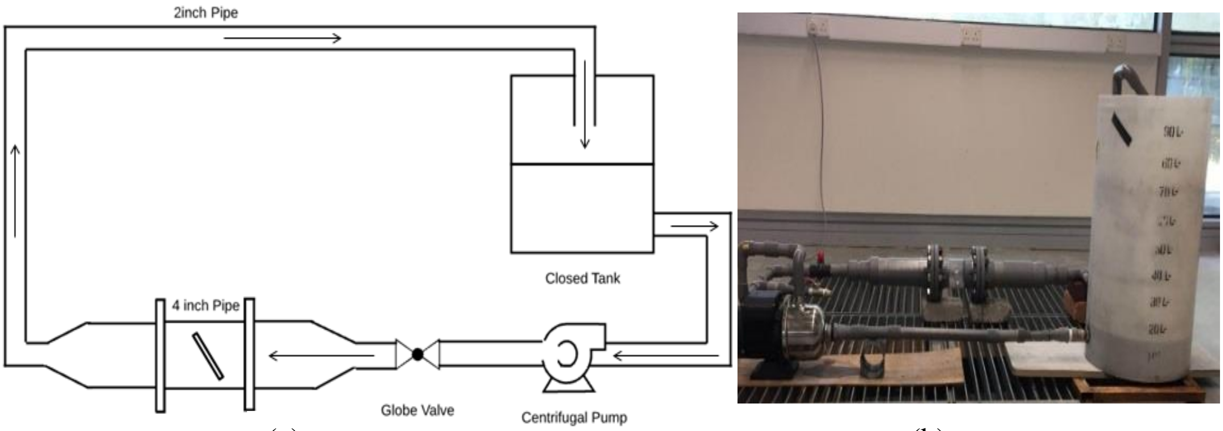
Equation (1.2) was introduced by [18]. When the particle to targeted surface hardness ratio is greater than unity, erosion will occur. Also, the erosion rate will escalate corresponding to the increase of erodent to target hardness ratio. Through the investigation of the impact of particle and target wall materials on particles erosion characteristics, [19] also perceived that the increase in hardness of erodent particles will develop its erosivity. However, there is a critical hardness value; beyond which the degree of erosion does not considerably increase with an increase of its hardness. This shows that sand erosion is susceptible to harder sand particles as they shatter less when colliding with target wall. Besides, another important factor in erosion calculation is density. This is because denser particles contain more kinetic energy, producing greater impact force and generating higher erosion rates [15, 20]. Therefore, hard and dense particles are inherently more erosive than soft particles. Typically, density of sand particles in various studies is approximately 2650 kg/m^3 [21, 22]. Erosion rate is a power-law function of particle impact velocity, defined as

$$\dot{E} = f\left(v_p\right)^m \tag{1.3}$$

3. Methodology

3.1 Experimental setup

The setup and design of the experiment to conduct a single phase flow wet sand impact erosion test is shown below. The schematic diagram and experiment setup of the experiment is shown in Fig. 3.



(a) (b)

Fig. 3: (a) Schematic diagram of the experiment and (b) Actual setup of the mixture flow loop

3.2 Sample preparation

The mild steel plates were cut into a square shape with a height of 50 mm and a length of 40 mm. The plates were cut by using an abrasive cutter machine. Then the mild steel plates were polished until they are free from scale, scratches and rough patches. The fine particles or silica samples average size of 60 µm were obtained from a ball mill factory. It is then mixed with water with fines to water ratio of 1:65 by weight.

Before and after the experiment, the specimen was subjected scanning electron microscopy to produce images for comparison. Energy Dispersive X-ray Spectroscopy (EDX) was also applied to the specimen before and after the experiments to analyse the differential chemical compositions of the exposed surface. The surface roughness of each mild steel plate were also recorded. The average surface roughness recorded before the experiment was found to be 0.17 µm. Finally, the specimens were subjected to Vickers micro hardness test to check the differential hardness of specimens before and after the experiments. The average hardness value recorded before the experiment was found to be 139.23 HV. This value is very close to the standard reference value 140 HV for mild steel.

The plates were placed inside the bombardment chamber at three different impact angles (-30°, 30°, 90° with respect to the horizon) and were bombarded with fluid containing fine particles with an average size of 60 µm for a fixed time interval of 5 hours. Due to the limitation of the test rigs capability, the flow rate and velocity of the fluid in the bombardment chamber were kept constant at 8.6 x 10-4 m3/s and 0.124 m/s respectively. The mixture filled up approximately 80% by volume when entering the bombardment chamber. The fluid hitting the mild steel plate inside the bombardment.

4. Results and Discussion

After 5 continuous hours of bombardment, the region of surface exposed to fine-water mixture showed observable and severe pitting, especially near the mixture free surface. Even though pitting is also observable at the bottom of the specimen, the distribution of the pits are scattered and the damage to the surface is relatively less. The level of surface damage was significantly influenced by the impact angles. From Fig. 4, the highest erosion rate was seen at an impact angle of 90° followed by -30 ° and finally 30 °. At 90°, the accelerated fluid containing fine particles does not exhibit any angular slip and imparted maximum energy to the surface of the mild steel plate. At inclined impact angles, the solid particles exhibited angular slip. The impact force by the particle can be split into axial and

IOP Conf. Series: Materials Science and Engineering **328** (2018) 012023 doi:10.1088/1757-899X/328/1/012023

vertical components. At inclined impact angles, the axial component is dominant and contributed to good amount of energy to the targeted surface. The energy transfer due to vertical component is almost negligible.

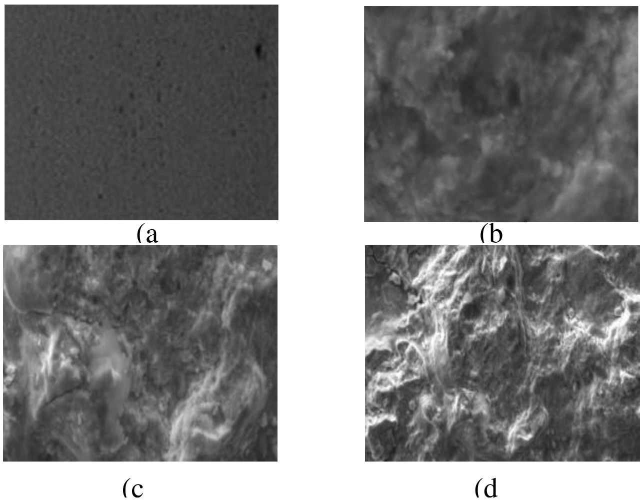


Fig. 4: (a) SEM micrograph of the untreated plate. (b) SEM micrograph of eroded plate at 30°. (c) SEM micrograph of eroded plate at -30°. (d) SEM micrograph of eroded plate at 90 °.

Figure 5: showed the EDX spectrum of the mild steel specimen before and after the experiment. It is clearly seen that before the experiment, the exposed surface showed composition of iron (Fe) and carbon (C) while after the experiment, the surface chemical composition of mild steel plates was significantly changed. It was noticed that some of the fine particles diffused onto the exposed surface of the mild steel plates. The new elements on the surface of the plates were believed to be introduced by the fines during the experiment. The EDX spectrum of the eroded specimen showed an additional two components, namely silicon and oxygen. This shows that erosion process does not only damage, the target surface it also changes its surface composition.

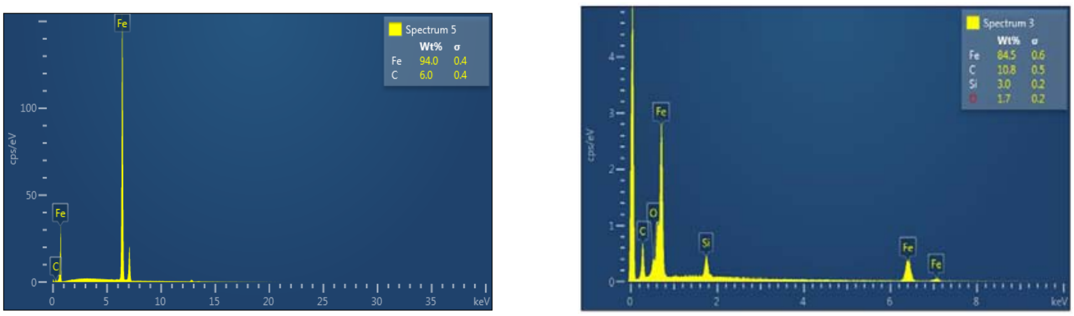


Fig. 5: EDX spectrum of mild steel specimen (a) before and (b) after experiment

Table 1 showed the surface roughness data for three specimens under investigation. The surface roughness of the specimens before experiment was determined to be 0.17 µm. After the experiments, the surface roughness of 30°, -30° and 90° were determined to be 0.56, 1.00, and 1.59 µm, respectively. The plate that was placed at an impact angle of 90° recorded the highest differential surface roughness, with change exceeded 800%.

Table 1. Surface roughness data

Impact angle (°)	Surface roughness (µm)			
	S1	**S2**	**S3**	**Average**
30	0.587	0.526	0.554	0.556
-30	1.032	1.043	0.929	1.001
90	1.678	1.505	1.572	1.585

The Vicker's micro hardness value of the treated samples as a function of impact angle is shown in Fig. 6. The non-eroded specimen was recorded with a hardness value of 139.23 HV. All three specimens recorded a reduction in their HV. The mild steel plate that was placed at an impact angle of 90° has the lowest hardness value followed by -30° and finally 30° which are 117.03 HV, 125.51 HV and 133.83 HV, respectively.

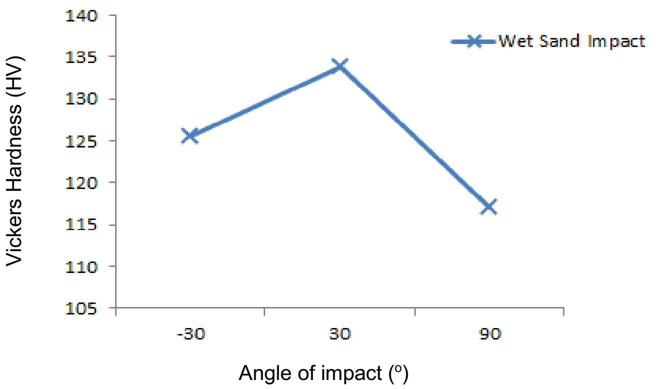


Fig. 6: Micro hardness of the eroded mild steel specimen

5. Conclusions

This study investigated the impact of wet erosion of mild steel, bombarded with water-fines mixture at three different impact angles which are -30°, 30° and 90°. The fines average particle is 60 µm and the water-fines mixture at a weight ratio of 1:65. It was found that the composition of the mild steel plates after the experiment changed significantly. Fine particles compositions were diffused onto the exposed metal surface. It could be concluded that fines changed mild steel surface roughness significantly, even for a short duration of 5 hours. A surprising 800% degradation of surface roughness was observed for 90° impingement. The hardness value of the specimen was observed to be reduced inversely proportional to the erosion.

References

[1] Kuncuro, B.; Ulummuddin, B.; Palar, S. (2011). Sand control for unconsolidated reservoirs. *ProceedingSimposium Nasional Yogyakarta*, 3.

[2] Carlson, J.; Gurley, D.; King, G. (2002). Sand control: why and how *Oil Field Review*, London.

[3] Naz, Y.; Ismail, N.I.; Sulaiman, S.A.; Shukrullah, S. (2015). Electrochemical and dry sand impact erosion studies on carbon steel, *Sci. Rep.*, 5, 16583.

[4] Finnie, I. (1960). Erosion of surface by solid particles, *Wear*, 3(2), 87–103

[5] Levy, A. (1995). *Solid particle erosion and erosion-corrosion of materials*. ASM International,Material Park, Ohio.
[6] Andrews, D.R.; Horsfield, N. (1983). Particle collisions in the vicinity of an eroding surface. *J. Phys. D: Appl. Phys*. 16(4).
[7] Chase, D.; Rybicki, E.; Shadley, J. (1992). A model for the effect of velocity on erosion of N80 steel tubing due to the normal impingement of solid particle. *J. Energy Resour. Technol.*, 114(1), 54-64.
[8] Hutchings, I. (1980). Some comments on the theoretical treatment of erosive particle impacts. In: Proceeding of the 5th International Conference on erosion by Liquid and Solid Impact, Newnham College, Cambridge.
[9] Jahanmir, S. (1980). The mechanics of subsurface damage in solid particle erosion. *Wear*, 61(2), 309-324.
[10] Kleis, I.; Kulu, P. (2008). *Solid Particle Erosion Occurrence, Prediction and Control*. Springer-Verlag London Limited. Library of Congress Control Number: 2007937988
[11] Srinivasan, S.; Scattergood, R.O. (1988). Effect of erodent hardness on erosion of brittle materials. *Wear* 128 (2), 139-152
[12] Sundararajan, G. (1991). A comprehensive model for the solid particle erosion of ductile materials. *Wear*, 149(1-2), 111-127.
[13] Winter, R. E.; Hutchings, I. M. (1974). Solid particle erosion studies using single angular particles. *Wear*, 29(2), 181-194.
[14] Levy, A.; Chik, P. (1983). The effect of erodent composition and shape on the erosion of steel. *Wear*, 89(2), 151-162.
[15] Parsi, M., (2014). *Sand erosion in vertical slug/churn flow*. Advisory Board Meeting, Erosion/Corrosion Research Centre, The University of Tulsa, May.
[16] Desale, G.R.; Gandhi, B.K.; Jain, S.C. (2009). Particle size effects on the slurry erosion of aluminum alloy (AA 6063). *Wear*, 266 (11-12), 1066-1071.
[17] Safaei M.R. et al., (2014). Investigation of micro- and nanosized particle erosion in a 90^o pipe bend using a two-phase discrete phase model. *The Scientific World Journal*, Vol 2014, ID 740678.
[18] Wada, S.; Watanabe, N. (1987). Solid particle erosion of brittle materials (part 3), the interaction with material properties of target and that of impingement on erosive wear mechanism. *Joural of the Ceramic Association Japan*, 95(10), 573-578.
[19] Shipway, P.; Hutchings, I. (1996). The role of particle properties in the erosion of brittle materials. *Wear*, 193(1), 105-113.
[20] Nicolici, S.; Prisecaru, I.; Dupleac, D. (2013). Two-phase flow CFD modelling for evaluation of particulate erosion. *U.P.B. Sci. Bull., Series D*, 75(1), 187-198.
[21] Chen, J.; Wang, Y.; Li, X.; He, R.; Han, S.; Chen, Y. (2015). Erosion prediction of liquid-particle two-phase flow in pipeline elbows via CFD–DEM coupling method. *Powder Technology*, 282, 25–31
[22] Najmi, K.; Mac Laury, B. S.; Shirazi, S. A.; Cremachi, S. (2016). The effect of viscosity on low concentration particle transport in single-phase (liquid) horizontal pipes. *ASME J Energy Resour. Technol.*, 138(3), 032902.