

EROSIVE WEAR OF NATURAL GAS PIPELINE

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Abstract. Erosive wear can be caused by a water jet burst from leaked water pipe laid side by side to natural gas pipeline. The erosive wear behavior of natural gas pipeline eroded by sand and water jetting was investigated. This work present the erosive wear analysis of API 5L X42, steel grade pipeline which normally used for distributing natural gas to an industrial customers by gas utility company in Malaysia. Tests were carried out by recreating above mentioned situation through the usage of 5 mm diameter orifice as the source of jetting in sand particles towards the pipe specimen that was buried at 1 meter depth. The existence of tunneling effect was established by identifying the horizontal and vertical tunneling through physical examination of the impacted surface. It was determined that the thickness of the pipe decreases with time. Determination of time taken for the pipe to rupture was established at 220 hours after continuous jetting and zero effect distance is at 450 mm from the jetting source of the relevant tests condition.

Keywords: Erosive wear; gas pipelines; slurry erosion; water jet; tunneling effect

Abstrak. Kakisan erosi boleh disebabkan oleh jet air yang terhasil dari paip air yang mengalami kebocoran yang berada pada kedudukan bersebelahan dengan talian paip gas. Kajian terperinci terhadap kelakuan kakisan erosive talian paip gas disebabkan oleh kakisan pasir dan jet air telah dijalankan. Kajian yang dijalankan membentangkan analisis kakisan erosive terhadap talian paip keluli gred API 5L X42, yang biasanya digunakan untuk sistem pengagihan gas asli kepada pengguna industri oleh syarikat pembekal gas di Malaysia. Beberapa ujian telah dijalankan dengan membina semula simulasi dan keadaan asal menggunakan orifis bergaris pusat 5 mm sebagai punca jet dalam partikel pasir, menghala ke spesimen paip kajian yang ditanam sedalam 1 meter. Kewujudan kesan terowong telah dikenal pasti melalui terowong mendatar dan pugak yang terhasil dalam ujian yang dijalankan dan kesan secara pemeriksaan fizikal ke atas permukaan hentaman. Ketebalan paip yang berkurangan terhadap sela masa dapat ditentukan melalui ujian tersebut. Masa yang digunakan bagi paip tersebut mengalami kebocoran adalah selama 220 jam selepas penjetan secara berterusan manakala jarak kesan sifar pula diperolehi pada jarak 450 mm dari punca jet dengan keadaan ujian berkaitan.

Kata kunci: Kakisan erosi; talian paip gas; erosi buburan; jet air; kesan terowong

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1.0 INTRODUCTION

Erosion is termed as degradation of an impacted surface by means of solid particles in fluid stream. Problem of erosion has long been an issue in the engineering world. Work on erosion by liquid impact has been studied by various researchers especially one related to the mechanical engineering field [1 – 2]. Liquid impact upon mechanical equipments or metals can be seen in forms of cavitations or metal degradation due to erosion. Among pioneer problems that resulted to this study is the fact that buried natural gas piping are always under the threat of damage due to water jetting in cases where water utility piping which runs parallel to it experience leakage. Degradation of piping material not only disrupts the continuity of natural gas supply; it too could pose a threat to life and buildings in terms of lost of lives and destruction of buildings. Cases of natural gas piping failure has been proven to be catastrophic as demonstrated in cases of pipe rupture in South Riding, Virginia in 1998 and Carlsbad, New Mexico in 2000 [3 – 4].

The problem of erosion has been discussed briefly in 1961 by S.M. DeCorso and R.E. Kothmann [5]. In this particular study it was concluded that erosion at high speed impact of greater than 700 feet per second can never be contributed by chemical action. Therefore, when chemical action was eliminated, the only possible causes that can be contributed to erosion of the blades are erosion due to mechanical action of the liquid impact during its operation. However a jet's ability to incur enough damage in terms of thinning of the impacted surface highly depends on the force of the impact. Force of an impact will vary with the distance away from the jetting source as every jet will have its own effective jet length [5]. In short, a jet which is not in its effective distance will produced damages that is less than the damages caused by a well formed jet at the same velocity. This can be explained by the area of the leading edge of the jet. An irregular shape for a jet's leading edge will not be able to produce an impact area which is as large as the one in its effective distance due to the area behind the leading edge has a reduced velocity compared to the leading edge. This happens as a result of momentum lost as the length traveled by the jet increased.

Referring to general belief, one normally expects a higher rate of deformation and erosion of a material which has a rough surface due to cavities or irregularity of impact surface. Unfortunately, the opposite has been found to be the real answer. For example, a test by having the surface area of impact to be placed by a single diamond point indentation will give a result which without a doubt rendered surface irregularity merely a minor effect to the overall damage done by the liquid impact [5].

Another unique characteristic that can be seen after a material has been deformed due to liquid impact is that it creates a ring deformation. The main feature of the deformation is a ring crack separating a region of intense circumferential fracture

from a central unfractured area of the surface [6]. Central unfractured area of the surface happens due to the displacing properties of the liquid impact. During the leading edge impact on the surface pressure generated by the impact velocity results to the exertion of enough force onto the surface to exceed the materials shear strength. The force will be displacing particles on the surface continuously and uniformly thus creating the central unfractured area.

Particles being displaced from the central unfractured area will be forced to move upwards towards the opening created by the liquid impact. This movement at high velocity resulted to the outer ring damages through shearing or tearing of the material surface. For the particles from the central area to move upwards it has to be at a velocity higher than the impact velocity. In short, the outer ring was damaged due to the radial force which is grater compared to the impact force due to increase of outward flow velocity [6].

Ductile materials refer to material which undergoes erosion process in the form of plastic deformation. Volume removal is normally due to the cutting or the displacing action of the solid particle in the liquid jet. Firstly it is to be expected that impact perpendicular to the surface would produce indentations but little volume removal in ductile material. However it is hardly the same for in cases where impact directions making a lower angle with the impacted surface due to the grooves which will be cut off the surface after the impact. Although it is true that little volume is removed when the impact is perpendicular to the impacted surface, one must not forget small cuts resulted from the impact can be aggravated when there are multiple impact as in the real situation of liquid jet [7 – 12].

In brittle material an entirely different result will be seen after an abrasive liquid jet impact. This is due to the fact that in brittle material erosion does not happen by means of plastic deformation but it is more likely related to the material's elastic behavior. Elastic stress of the impacting particles will contribute to the displacing action of the particle through propagation and intersection of cracks ahead of the impacting particles. It is found through a test that brittle material erodes most rapidly at angles near to 90 degree [7, 10]. The explanation for this is that in brittle material angle of 90 degree for the impacting particle with the impacted surface allows a maximum component of velocity tangential to the surface with regard to angular particle. This maximum tangential velocity will be able to exert enough force to firstly propagate cracking of the impacted surface [10 – 11].

In this work, erosive wear of API 5L X42, carbon steel natural gas pipe is presented. The discussion will emphasized on the erosion effect, thinning rate through the usage of 5 mm diameter orifice as a jetting source of 10 bar water jet pressure at fixed distance of 300 mm. Optical microscopy and digital ultrasonic thickness gauge were performed to characterize the pipe material and established the erosion rate of the tested pipeline.

2.0 EXPERIMENTAL

2.1 Basic Concept

Experiment was conducted by utilizing a compartment (experimental tank) to simulate a buried piping system. Figure 1 is a diagram depicting the basic idea of the experiment. The piping system need not be an elaborate piping system as it is sufficient that a section of a pipe is buried in the compartment to symbolize a working buried natural gas piping. Fine sand without gravels was filled into the compartment thus burying the pipe. This sand will act as the erosive particles to be present in the water jet. Water jetting effect was created in the compartment by using different sizes of orifices pointing towards the buried pipe.

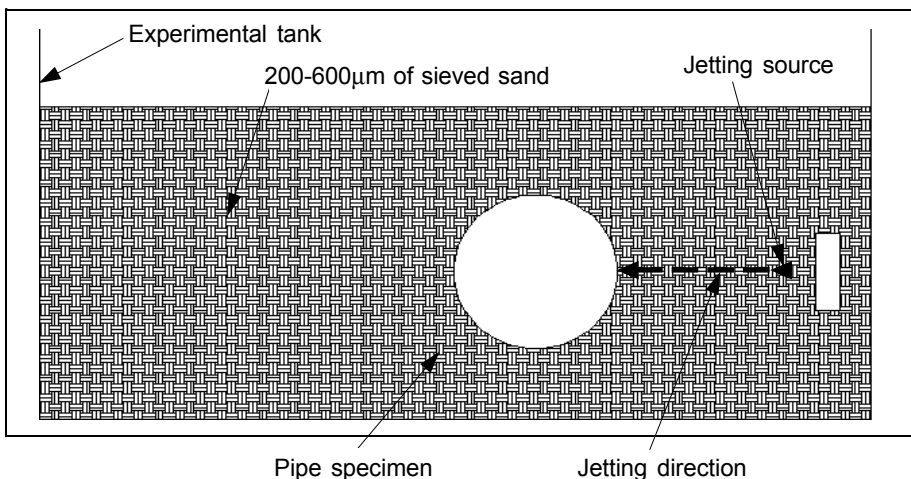


Figure 1 Basic concept of experimental apparatus

2.2 Experimental Rig

A section of natural gas pipe was attached to the saddle on the rig. The saddle was adjusted to a distance deemed suitable for the experiment. An orifice was attached to the orifice holder. Supply pressure of the water was set at 10 barg while the distance away from the jetting source was varied at 10 cm till 70 cm. Sieved sand particles of 600 – 2000 µm were the erodents was filled into the handling tank before the rig was lowered into the tank. A number of small holes drilled on the rig structure that will act as a repellent which creates small jet-push effect to disperse sand in the tank to allow the rig to be lowered down into the sand thus burying it. After the designated interval the rig was lift-out from the handling tank using a chain block system. Thinning of the sample pipe material was measured on points dictated

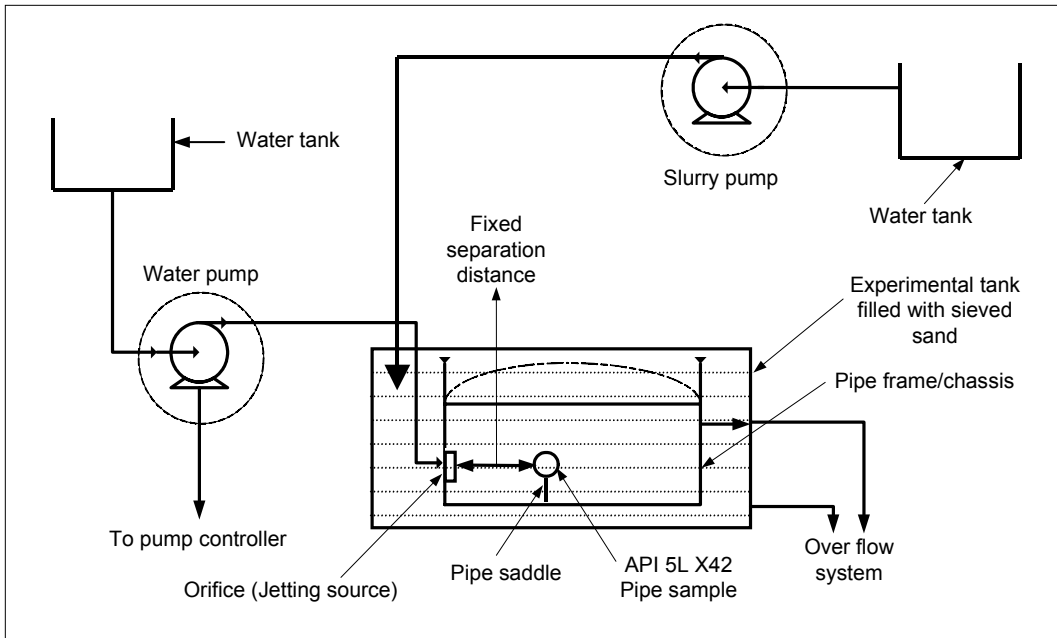


Figure 2 Experimental set up

based on a data-taking template. Figure 2 is a schematic diagram represents the use of experimental rig in the current study.

2.3 Pipeline Specifications

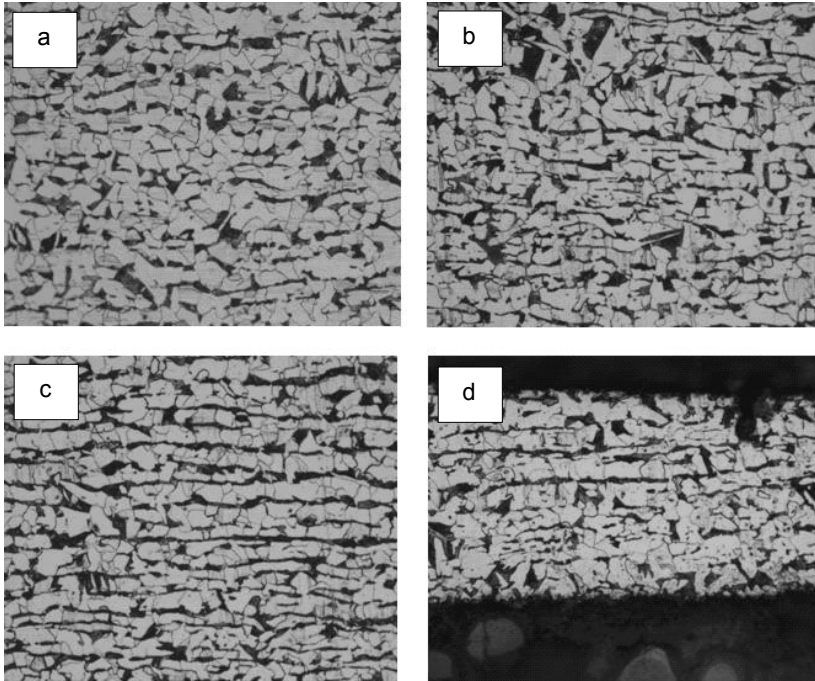
Mechanical and operating data of the pipeline are summarized in Table 1. The pipe had been manufactured by Sumitomo Metal Industries, Japan. The pipeline has been tested hydrostatically at the mill for 15100 kPa on August 3rd 2003. Table 2 shows the chemical composition of the pipe. The optical microscopy study shows that the metal base of the pipeline is a typical ferrite and pearlitic microstructure which is of a typical API 5L X42 steel grade. Figure 3 shows a metallographic micrograph of the gas pipe. The pipe section was cut, hot mounted in a thermosetting plastic using hot mounting press and then metallographically ground and polished

Table 1 Mechanical and operating data of pipeline

Grade of steel	API 5L X42 , 42,000 psi min, yield
Type of pipe	Seamless
Material	Black carbon
Diameter	219.10 mm
Wall thickness	5.6 mm
Hydraulic pressure (factory tested)	15100 kPa

Table 2 Chemical composition (wt%) of gas pipeline

Sample	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	Ti	Co	B	Ca	Al
0.18	0.22	0.84	0.013	0.004	0.03	0.07	0.02	0.01	0.001	0.06	0.0001	0.00023	0.03	

**Figure 3** Microstructures of the gas pipe showing pearlite bands phase in the ferrite matrix, at 200 \times

using the grinding and polishing wheels. In order to reveal the microstructures of the specimen were subjected to an etching process in 2% of nitric acid with 98% of methanol. The prepared specimens were then examined with 200 \times magnification using optical metallographic microscope.

2.4 Methodology for Evaluation of Wear

2.4.1 Data Taking Template

The thickness of the coating and thickness of the pipe without the coating was measured by thickness measuring equipment. All the data for the coating thickness and the thickness of the pipe without the coating were recorded. Several sets of measurement data for every specimen were taken in order to obtain an accurate and minimum error in reading.

The surface of the pipe specimen was divided into 4 horizontal sections with 5 horizontal lines, namely Line A, Line B, Line C, Line D and Line E. Next, the horizontal lines were separated into 3 areas with the data taking points being the center of the area. Coating thickness data on each area were acquired using digital coating thickness gauge. In order to determine metal thickness of each specimen, a section of the specimen were coating scraped off to reveal the bare metal surface of the specimen. Three data measurement were taken from the designated point as shown in Figure 4. Once all the procedures have been accordingly followed correctly, the specimen is tied to the pipe holder rig. The position of the specimen is requiring adjustment in order to ensure the jetting of the orifice is parallel to the line and points that have been selected as the surface of the specimen.

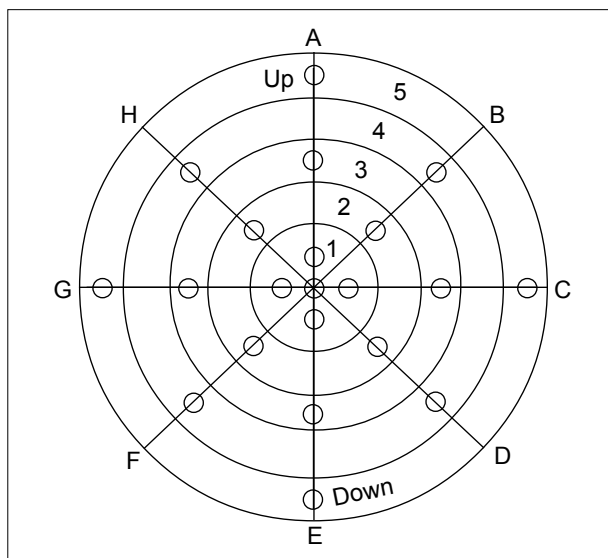


Figure 4 Data taking template

2.4.2 Visual Inspection

This was done through visual inspection of the impacted surface after the end of testing which coincides with the identification of rupture point on the specimen surface. Besides visual inspection, physical examination too was administered through the act of touching the impacted surface with bare hands to determine the surface roughness.

2.4.3 Determination of Metal Thinning

Metal thinning effect was monitored through specimen thickness measurement after a period of jetting exposure. Thickness measurement gauges used in the experiment

consisted of two types. First is the Digital Coating Thickness Gauge (Model TT260) used in measuring the thickness of the pipe's coating. While the thickness of the bare pipe is measured using the Digital Ultrasonic Thickness Gauge (Model TT130).

3.0 RESULTS AND DISCUSSION

3.1 Visual Analysis Of The Impacted Surface

From physical examination it was clearly observed that orifice jetting produces an impact on the specimen pipe which resembles a round shape. One thing peculiar about the impacted surface is that the roughness of the impacted surface is not evenly scattered. This is indicated by the existence of two distinct areas on the specimen's surface, with one being smooth while the other being very rough. Figure 5 below depicts a specimen surface after an exposure of 170 hours to erosive jetting.

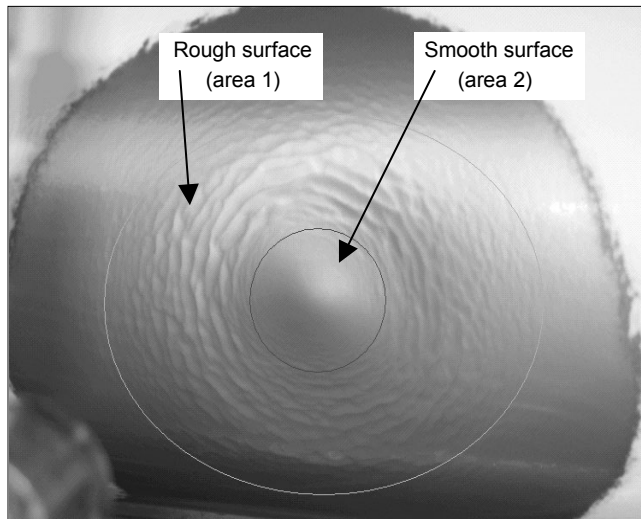


Figure 5 Specimen surface after impact

Those two areas could be characterized as the one where only water is the majority as the erosion media while the other sand is seen as the majority of the erosion media. The one which has water as the main erosion media has a smoother surface when compared to the one which has sand as the main erosion media. In order to explain this phenomenon it is imperative that Figure 6 to be referred to.

Area 1 is the one that has water as the majority erosion media. This has occurred due to the fact that the velocity of that area is higher compared to the velocity of Area 2. Difference of velocity resulted to the difference of sand carrying ability of the water jet. Sand carrying ability is the ability of the water jet to carry as much as possible of the abrasive media which in this case are the sand particles.

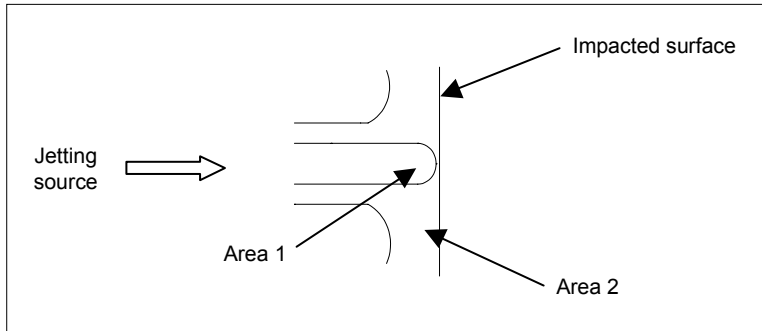


Figure 6 Orifice jetting profiling

In this particular case, the velocity of the various areas in the water jet resulted to the difference in the abrasiveness of the water jet. For example, velocity of the orifice outlet in Area 1 was found higher compared to the one in Area 2. Therefore its ability to carry sand particles is subsequently reduced due to the weight of the sand which reduces the sand particles' ability to move with high velocity as in Area 1. Theoretically this could be verified with the equation below;

$$F = ma \quad (1)$$

Where: F is force; m is mass; and a is acceleration.

From the above equation given, it is safe to agree upon the fact that an increase in mass will result to the reduction of the sand particles' ability to accelerate in order to achieve the sufficient force to be at the velocity needed to move in Area 1. Bearing this in mind it is not entirely misleading if it were to be concluded that the existence of two different category of area upon the impacted surface is due to the way of the sand particles' dispersion and concentration of the water jet in various area.

3.2 Water Jet Dispersion Profiling

According to Figure 5, divergence away of the jet from its center point does occurred as the mark left upon the impacted specimen is larger than 5 mm diameter that bears the size of the orifice. Dispersion of water jet structure away from its center point is basically due to the high resistance of the initial impacted media which in this case is water impacting on sand particles.

It is already explained that the center point of the jet will have a higher velocity compared to the points away from it. Area away from the center point will have a lesser force to comprehend the obstruction of the initial impacted media. This failure resulted to the jet not being able to go further forward towards the specimen thus dispersing upwards or downwards according to its location away from its center point where the resistance is less due to the turbulence flow in the impacted media.

The turbulent flow is a result of the jetting pushing aside the impacted media away from obstructing it from moving forward. In order to further understand this phenomenon, Figure 7 shows the characteristics of jetting in water to water system.

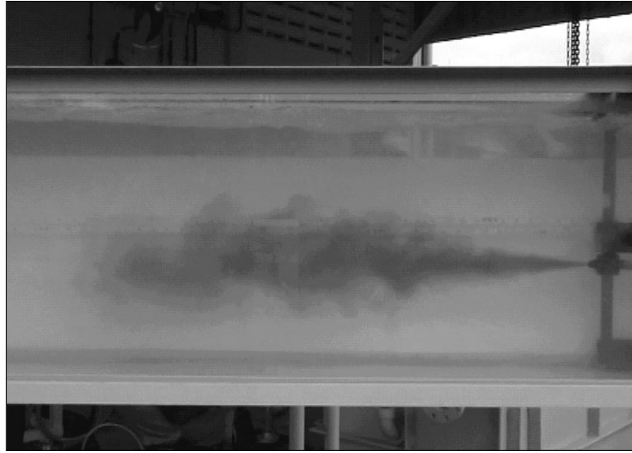


Figure 7 Water to water jetting profile

3.3 TUNNELING EFFECT

Tunneling effect could be describe as a pathway created due to the dispersion of sand to give way for water jet which has a high velocity. During the experiment two types of tunneling effect was identified. First being the horizontal tunneling and vertical tunneling being the later. Figure 8 shows how tunneling effect was formed.

This diagram shows that the existence of the vertical tunneling is due to the upwards movement of the jet after it has been impacted upon the pipe surface.

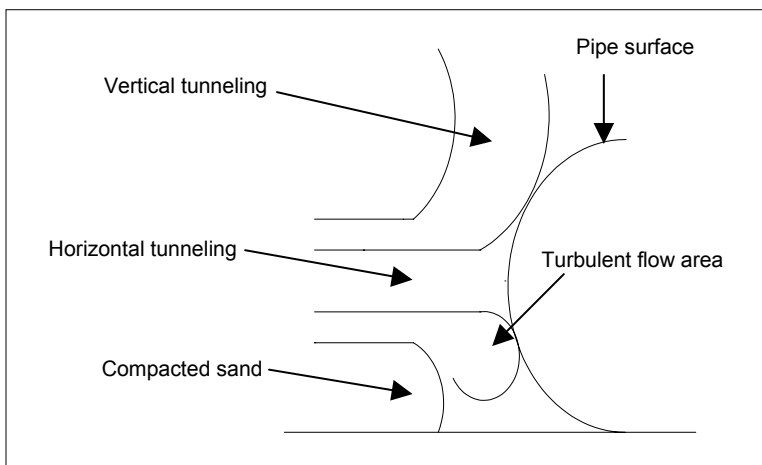


Figure 8 Tunneling profiling

Following the pipe curvature the upwards flow is a lot evident compared to the downward flow direction. This phenomenon is contributed to compact sand resistance on the upper side of the pipe that is significantly lower compared to the one beneath it. Compacted sand above the pipe can be easily dispersed due to the condition above the pipe being in the manner of an open system which has direct contact with the atmosphere. Upward movement of the jet resulted to the gradual collapsing of the sand structure above the pipe specimen. This in time will bring upon a hollow like vertical tunnel which allows the movement upwards steadily without much resistance.

Horizontal tunneling existence can be explained by observing the nature of sand dispersion. When water jet is out of an orifice, it will push aside sand particles near the outlet of the orifice. Due to its high velocity, the water jet will act like a solid thus providing enough force to push away sand particles from blocking its way. This could only occur when there is enough force in the jet itself but any reduction in the force of the jet will result to the mixing of the sand particles into the water jet thus forming an abrasive water jetting.

Proof of the mixing of sand particles with the water jet can be seen through the identification of the rough surface upon the impacted surface and this is especially true as there are two different areas on the impacted surface. They are the smooth inner area and the rough outer area. This is inline with the jetting characteristics explained earlier. Characteristics of the jet stipulate that the round shape on the specimen's surface were due to the shape of the impacted jet. Thus it is not being far from the truth for us to conclude that the smooth surface upon the impacted surface was a result of horizontal tunneling as the smooth area on the impacted surface confirms that there were almost zero sand particles present at the point of impact giving an impression of a hollow like structure formation from the orifice outlet which resembles a tunnel.

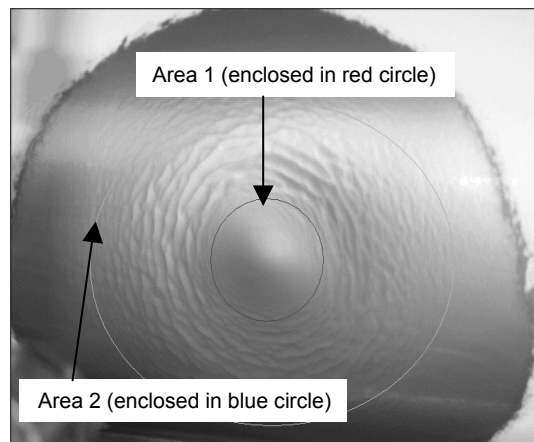


Figure 9 Tunneling effect on pipe

It could postulate that the shape of the horizontal tunneling depends on the type of jetting apparatus used. As tunneling created by the 5 mm orifice from a distance of 20 cm away from the jetting source is round in shape. Diameter of the tunneling on the specimen impacted by water jet from the orifice around 5 cm. Figure 9 shows the tunneling diameter (area 1).

3.4 Specimen Thickness and Time Relationship

Generally, it could be seen that the relationship between pipe thickness and time is inversely proportional from each other. Pipe thickness is seen to be decreasing with the increment of time. This is significantly implied due to the fact that the pipe is being eroded by the erosive water jetting throughout the experiment.

From physical examination of the graph to be presented (Figure 10 to 14) it could be concluded that the rate of thinning in Zone 1 is higher compared to the rest of the lines regardless of the lines on which the points are located. This could be explained by the fact that during the jetting operation, tunneling effect was present. Thus, Zone 1 eroded at a higher rate compared to the rest of the zone. This phenomenon is largely contributed by the erosive sand slurry thus hampering its thinning rate compared to the points in Zone 1 which coincides with Area 2 of the tunneling created. Figure 10-14 illustrates the relationship between thinning rate and orifice jetting time.

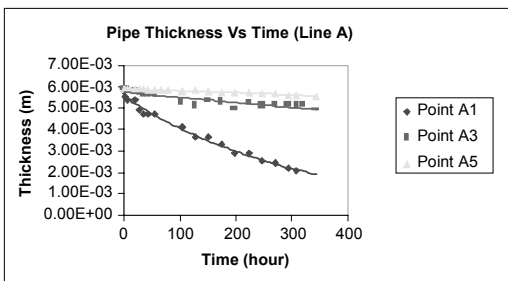


Figure 10 Analysis of Line B

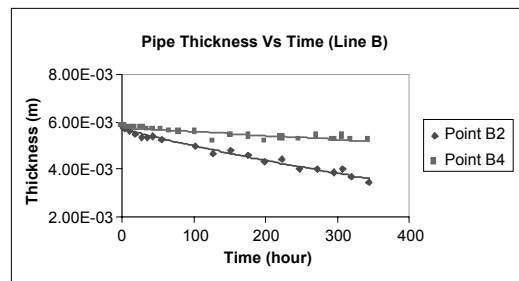


Figure 11 Analysis of Line A

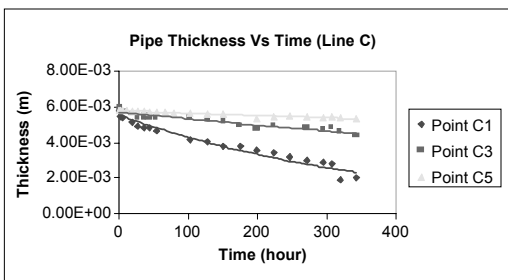


Figure 12 Analysis of Line C

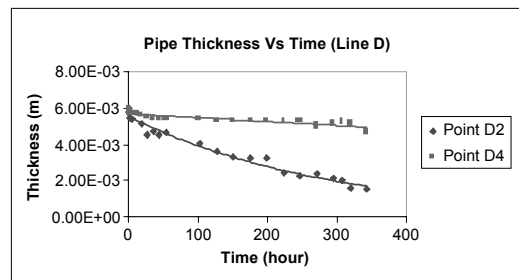


Figure 13 Analysis of Line D

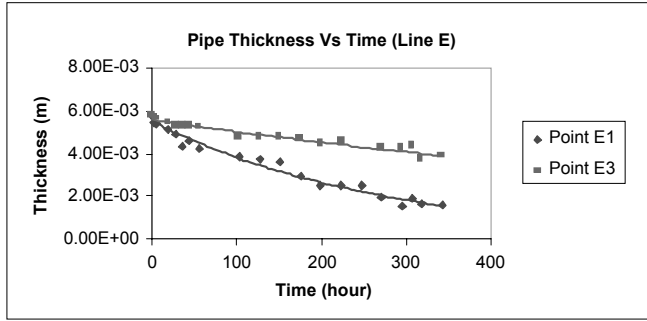


Figure 14 Analysis of Line E

3.5 Specimen Thinning Effect Dispersion

In order to determine the average thinning rate of each point, the initial pipe thickness reading is subtracted by the last pipe thickness reading and divided by the total period of experiment. Table 3 is a table denoting each point's thinning rate for orifice water jetting. Points indicated in the table were based on the points marked rendered by the designed template shown in Figure 4. The table clearly showed that the highest thinning rate is in the line E region while the lowest thinning rate is evident in the line A region. This could be explained by the existence of vertical tunneling near Line A region and turbulent flow area near line E region as previously shown in Figure 8.

Table 3 Average thinning rate of orifice jetting

Point	Average thinning rate (m/hr)
A1	1.08×10^{-5}
A3	2.87×10^{-6}
A5	1.01×10^{-6}
B2	6.84×10^{-6}
B4	1.60×10^{-6}
C1	1.10×10^{-5}
C3	4.46×10^{-6}
C5	1.41×10^{-6}
D2	1.23×10^{-5}
D4	3.28×10^{-6}

As explained before, upward movement of the jet resulted to the gradual collapsing of the sand structure above the pipe specimen. This in time will bring upon a hollow like vertical tunnel which allows the movement upwards steadily without much resistance. Bearing this in mind that it is not entirely surprising that the thinning rate

in line A is lower compared to the rest of the lines. As the vertical tunneling allows minimum contact between abrasive media with surface in line A region. The explanation for this is that the mass of the sand particles is way too high for it to move upwards following the vertical tunneling.

The thinning rate of line E region is highest due to high turbulent flow. In this area movement downwards is being resisted by the compacted sand beneath the pipe specimen. This resistance is in the manner of a closed system thus restricting the displacement of sand downwards. Resulting from this is the circular flow of abrasive material in the water jet nearing line E region as the water jet's flow is being resisted by the compacted sand beneath the pipe specimen. In time this circular flow will aggravate and accelerate the erosion on that area which resembles grinder being impacted upon a solid surface continuously.

Besides the effect of turbulent flow in line E region, one must never forget the existence of gravitational effect. Thus, the sand with high mass would not be able to travel upwards without being pulled downwards by the gravitational force, and subsequently stays near line E region, with higher acceleration thus creating a higher concentration of abrasive material. The obvious proof that line E region has a higher thinning rate is the fact that the rupture point during the experiment lies within line E shown in Figure 15.

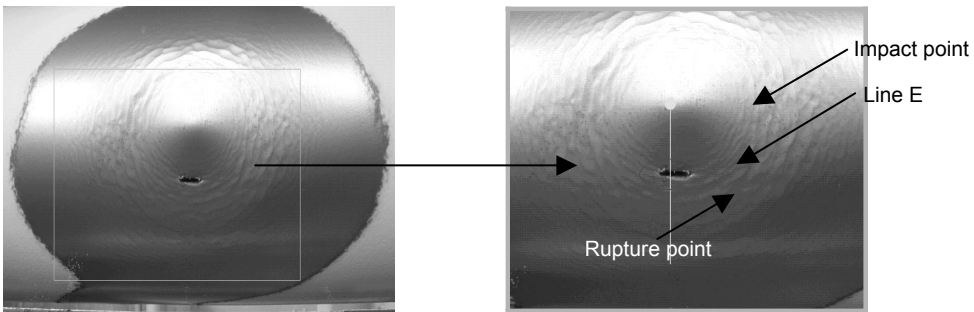


Figure 15a Picture of ruptured specimen

Figure 15b Close-up of the rupture point – blue enclosure

From the earlier observation made, it is true that the area with the thinning rate or the rupture point coincides with line E region due to the turbulent area within its vicinity. The rupture took place after almost 220 hours (Figure 16).

3.6 Zero Effect Distance

This experiment has been conducted in slurry system (water-to-sand), where the high pressure of water is pushed into compacted sand environment. The purpose of conducting this experiment is to estimate safe distance of no abrasive effect of water jetting upon surface of impact.

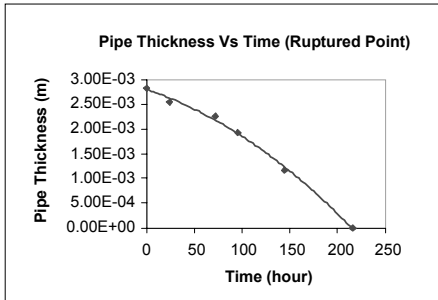


Figure 16 Thickness loss versus time for rupture point

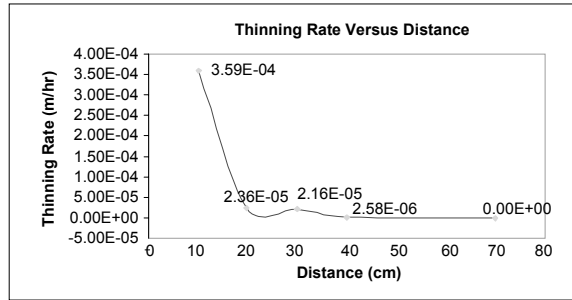


Figure 17 Thinning rate versus distance

Figure 17, indicates that the relationship of thinning rate versus the distance from the outlet of a 5 mm diameter orifice is inversely proportional from each other. The increase in distance will eventually reduces the thinning rate of the specimen. It could also be identified that the abrasive effect of the jetting stops completely at a distance of 70 cm away from the jetting source. The trend of the graph indicates that the distance of abrasive effect upon the impacted surface stops at around 45 cm away from the point of jetting. The separation distance shows that a gas piping surface must be of at least 300 mm away from piping surfaces which runs parallel to it. This in practice is clearly insufficient in curbing the problem of erosive water jetting.

4.0 CONCLUSION

The erosion-abrasion-water-jetting effect does significantly contribute to the thinning rate of natural gas piping. An increase in time exposure significantly resulted to the decrease of specimen thickness. The existence of two distinct patterns on the impacted surface shows the effect of abrasive material dispersion is closely related to the velocity of the jet in its centerline region and region further away from its centerline. Pattern of impact and the dispersion of metal thinning showed the existence of vertical and horizontal tunneling due to velocity differences and gravitational effect. The study was also able to demonstrate that the pipe will be ruptured after 220 hour of exposure time to the water jetting and the zero effect distance away from the point of jetting of 5 mm orifice diameter to be around 4500 mm.

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