A NOVEL LEAK DETECTION IN OIL PIPELINE USING MODIFIED DARCY-WEISBACH EQUATION

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Abstract

The safety of oil and gas pipelines is of utmost importance to pipeline operators. This is due to the importance of the product, the financial loss and damages associated with ruptures of oil and gas pipeline. People usually break the pipeline and siphon huge quantities of crude and sell it in the black market at a much lower price. Though, a lot of techniques has been developed to detect and localize leakages in pipeline on time to prevent theft and spillage, a new technique is now being used in Nigeria to siphon oil from pipeline without being easily detected. This research follows a similar study conducted on gas pipeline using modified panhandle B equation. We discovered that if during pipeline down time or induced down time due to sabotage from pipeline staffs, and a long host is forged into a gas (methane) pipeline for gas theft, the change in flow rate is almost unchanged (for small leak) that control room engineers term it **'small or no leak'** when gas is being taken away from the pipeline. For large leak diameter, the flow rate depreciates greatly and appreciates instantly as though it is a pressure surge. We got a similar result on oil (gasoline) pipeline using **modified Darcy-Weisbach equation**.
Keywords: Pipeline leak detection, Darcy-weisbach equation, Panhandle B equation, Pipeline down time, pressure surge.

1. INTRODUCTION

Pipeline networks are the most convenient and safest mode of conveying oil, gases and other fluid products from one point to another. Their importance in modern societies cannot be overemphasized as they play a vital role in the provision of energy needed for economic activities such as power generation, heating supply, and transportation [1]. The structural integrity of a pipeline borders on the ability to meet high demands of safety, reliability and efficiency, as a means of long-distance transport. Pipelines through proper maintenance can last for long time without a leak. Otherwise, it can begin to corrode slowly, particularly at construction joints, or low points where moisture collects, or locations with imperfections in the pipe.

Pipeline failure as detailed by [2] is caused by corrosion, excavation damage, incorrect operation, material/weld/equipment failure, natural force damage, other outside force damage and all other causes. It highlighted that the two prominent causes of significant pipeline incidents in all pipeline systems, including hazardous liquid, gas transmission, gathering, and gas distribution systems are excavation damage and corrosion. Achebe[1] in his analysis of oil and gas pipeline failures in the Niger Delta area of Nigeria discovered that the major causes of pipeline failures in the area are; ageing, corrosion, mechanical failures such as welding defects, pressure surge problems, stress, and wall thickness. Jasper[3] in his assessment of potential leak detection technologies in Niger Delta region of Nigeria, categorized causes of pipeline failures into four; Operational, structural, unintended or intended damages. In Nigeria, there is high deployment of pipeline infrastructures in Niger Delta area, making it highly vulnerable to pipeline vandalism. This was x-rayed by Yo- Essien[4] of NOSDRA when he noted that most pipeline incidents that occur along major pipelines and manifolds are caused by vandalism in Nigeria.

However, this paper will not look at the analysis of pipeline incidences in Nigeria. The main objective of this paper is to open the eye of major stake holders in pipeline industry of the new technique used in Nigeria to steal from Oil pipeline. It is usually carried out as a coordinated attack in oil pipeline and is done in collaboration with pipeline staffs. This involves pipeline engineers/operators deliberately inducing

downtime on pipeline leaving their accomplices to forge a long pipe on pipeline in remote locations. The pipe is taken to a secluded building where Oil theft is carried out for years without people knowing as shown from the Matlab simulation result using modified darcy-weisbach equation. It is a novel leak detection in Oil pipeline.

Mathematical models have been developed to predict flow variations such as pressures and flow rates at the ends of a pipeline in case a leak occurs. Thus loss/damages caused by a leak can be evaluated using these models which can also provide a guide for pipeline operation. Liang [5] formulated a new approach for analyzing a pipeline with a leak by formulating an electrical equivalent of mathematical flow models and carried out validation with. a real oil pipeline. These models have the ability to generate test data that can be used in validating the model based leak detection and location methods [6].Apart from mathematical modeling, there are so many other techniques being used to detect and localize leakages in pipeline. LDS(Leak detection systems) help pipeline controllers in detecting and localizing leaks. They provide an alarm and display other related information to the pipeline control room staffs in order to aid in taking decision. LDS Systems are thus, an essential aspect of pipeline structural integrity and technology. According to the API document "RP 1130", LDS Systems are divided into internally based LDS Systems and externally based LDS Systems[7].Internally based systems utilize field instrumentation (for example flow, pressure or fluid temperature sensors) to monitor internal pipeline parameters. The externally based systems also utilize field instrumentation (for example infrared radiometers or thermal cameras, vapor sensors, acoustic microphones or fiber-optic cables) to monitor external pipeline parameters.

Zhang [8] classified pipeline leak detection into biological, hardware-based and software-based method. Biological method involves detection and localization by inspection of pipeline using trained personnel or dogs to sense odour or sound in the surrounding pipeline leak. This biological method is also referred to as the non-technical method [9].The hardware-based method involves using physical devices such as; visual devices, gas sampling devices, pressure wave detectors, acoustic devices, optical devices, cable sensor etc to detect and localize leaks. Visual devices make use of changes in the temperature of the immediate vicinity of the pipeline to detect leakage. Weil [10] developed infrared thermography to detect leak in hot water pipeline when the temperature of the surroundings increased after a leak developed. Turner [11] detected the changes of temperature in the neighborhood of a leak by means of a temperature sensors such as multi-sensor electrical cable and optical time domain reflectometry using fiber optic cables. In pressure wave detection, the negative pressure associated with a leak is propagated as sound both upstream and downstream from the leak site. Using pressure transducers, one can measure the pressure gradient with respect to time[11]. In acoustic method of hardware-based, a leak is propagated as noise or sound waves as the fluid escapes from the pipeline. The propagation wave or the speed of sound is dependent on the material and pipe diameter based on Thorley[12]. Whenever a leak occur, a break in pressure balance occur and the difference is propagated as acoustic signal both upstream and downstream[13]. The stress wave that is transmitted through the pipeline can be recorded by acoustic sensor or accelerometer[14]. Acoustic sensors are normally installed outside the pipeline network and they pick up noise generated by leaks. Thus, they are external based leakage detectors.

Software-based method uses various computer software packages to detect leaks in a pipeline. They use flow, pressure and other data provided by a SCADA systems to detect leakage[15]. Some of the software technique includes; flow or pressure change, mass or volume balance, dynamic model based system, pressure point analysis, statistical and digital signal processing. Pressure or flow change assumes any high discrepancy in pressure or flow rates at upstream or downstream indicates a leak. There is a generation of leak alarm when the difference is considerably higher than a set threshold within a specific time period. The mass or volume balance generates a leak alarm when the difference between an inlet and outlet flow measurement changes by more than a set threshold. This method can be based on flow difference only which would generate a simple mass or volume balance scheme or on flow difference compensated by pressure/temperature changes and inventory fluctuations in pipeline[16].

In dynamic model based system, fluid flow within a pipeline is modeled mathematically and leaks are detected based on differences between calculated and measured values[17].Equations such as; conservation of mass, energy and momentum, equation of state for the fluid, etc are used. The pressure point analysis is based on assumption that the occurrence of a leak in a pipeline leads to drop in pressure on the pipeline. If the decrease is more than a predefined level, then a leak alarm is generated. The statistical method is a non-mathematical technique in which an advanced pattern recognition functions is incorporated in a pipeline. Usually, some parameters like pressures and flow rates at various locations along the pipeline are measured and a leak alarm is only generated if it encounters certain patterns of relative changes in pressure and flow[18]. The signal processing technique does not also need the mathematical model of the pipeline. The major purpose is to extract leak information from a noisy data. It was first proposed for liquid pipelines [19].

2. METHODOLOGY

2.1. PRESSURE LOSS DURING LAMINAR FLOW IN A PIPE

The pressure loss in a pipe with laminar flow is given by the Hagen-Poiseuille equation:

$$\Delta P = \frac{32\mu L U}{D^2}$$

1

Or in terms of head

$$hf = \frac{32\mu L U}{\rho g D^2}$$

2

2.2. PRESSURE LOSS DURING TURBULENT FLOW IN A PIPE.

For turbulent flow, the head loss is given by Darcy-weisbach equation often referred to as the "Darcy equation.

$$hf = \frac{4fLU^2}{2gD}$$

3

F=frictional factor in pipe.

The darcy equation is equivalent to the Hagen-poisuille equation for laminar flow with the exception of the empirical friction factor f introduced. Writing Darcy equation in terms of discharge (using Q=Au)

$$\Delta P = \frac{4Q}{\pi D^2}$$

4

$$hf = \frac{64fLQ^2}{2g\pi^2 D^2} = \frac{fLQ^2}{3.03D^2}$$

5

Or with a 1 percent error

$$hf = \frac{fLQ^2}{3D^2}$$

6

2.3. THE VALUE OF F FOR LAMINAR FLOW

The equation derived for head loss in turbulent flow is equivalent to that derived for laminar flow with the only difference being the empirical F. To apply the darcy equation to laminar flow, we can derive an expression for f by equating the head losses of eq.(2) and eq. (3)

Equating the Hagen-Poiseuille and Darcy-Weisbach equations gives:

$$\frac{32\mu L U}{\rho g D^2} = \frac{4fLU^2}{2gD}$$

$$f = \frac{16\mu}{\rho v D} = \frac{16}{Re}$$

7

2.4. COLEBROOK-WHITE EQUATION FOR FRICTIONAL FACTOR F.

Colebrook and white performed a good number of experiments on commercial pipes and also brought together some important theoretical work by von Karman and Prandtl. This work resulted in an equation attributed to them as the Colebrook-White equation[20]:

$$1/\sqrt{f} = -2.0\log 10\left[\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right)\right] \quad 8$$

2.5. MOODY EQUATION AND DIAGRAM/CHART

The Moody chart or Moody diagram is a graph in non-dimensional form that relates the Darcy-Weisbach friction factor, Reynolds number and relative roughness of pipe for fully developed flow in a circular pipe. Moody made a useful contribution to help, he plotted f against Re for commercial pipes and the figure has become known as the Moody Diagram[21]. He also developed an equation based on the Colebrook-white equation that made it simpler to calculate f:

$$f=0.001375\left[1+\left(\frac{200\varepsilon}{D}+\frac{106}{\mathrm{Re}}\right)^{1/3}\right] \quad 9$$

3. MODIFICATION OF THE DARCY WEISBACH EQUATION FOR LEAKAGE DEFECTION IN PIPELINE.

Recall, from eq. (6), $hf=\frac{fLQ^2}{3D^2}$

But $\Delta p = \rho gh$. Replacing h in this equation and making Q the subject gives

$$Q_1=\left[\frac{3(P_1-P_2)D^5}{\rho gfl}\right]^{1/2} \quad 10$$

That is the flow rate for a pipeline at full capacity (Fig 1). Ie no leak.

According to Crane [22], if the pressure drop in a pipeline is less than 40% of inlet pressure, Darcy-Weisbach incompressible flow calculation may be more accurate than the practical gas equations for a short pipe or low flow. The Darcy equation is valid for any flow rate, diameter, and pipe length, but does not account for gas compressibility. If the pressure drop is less than 10% of P_1 and you use an incompressible model, then the gas density should be based on either the upstream or the downstream conditions. If the pressure drop is between 10% and 39%, then the density used in an incompressible flow method should be based on the average of the upstream and downstream conditions.

Assuming a pressure drop of 20% of inlet according to Crane above,

$\Delta P = 20\% \ P_1 \Rightarrow P_1 - P_2 = 0.2P_1$

$\therefore \ P_2 = 0.8P_1$

Eq. (10) becomes

$$Q_1=\left[\frac{0.6P_1D^5}{\rho gfl}\right]^{1/2} \quad 11$$

The pipeline is opened for leakages as shown in Fig 2.

The diameter of leak is (d) and the leak thickness or inserted pipe length is (x). The flow rate (q) in the inserted length is given by

$$q=\left[\frac{3(P_2-P_3)d^5}{\rho gfx}\right]^{1/2} \quad 12$$

$P_3 = 0.8P_2 = 0.8\ (0.8P_1) = 0.64P_1$

$\therefore \ P_2 - P_3 = 0.8P_1 - 0.64P_1 = 0.16P_1$

$$q=\left[\frac{3(0.16P_1)d^5}{\rho gfx}\right]^{1/2} \quad 13$$

$$q=\left[\frac{0.48P_1d^5}{\rho gfx}\right]^{1/2} \quad 14$$

With leakage, the overall flow rate is given by

$Q = Q_1 - q$

$$Q=\left[\frac{0.6P_1D^5}{\rho gfl}\right]^{1/2}-\left[\frac{0.48d^5}{\rho gfx}\right]^{1/2} \quad 15$$

This equation is converted to barrel per day as follows,

1day=24×3600s; 1s = 1/24×3600day,

$1m^3$ =6.29barrel,

$1m^3/s$ = 6.29×24×3600 =543456B/D,

Substituting into the above eq. (15) gives

$$Q=543456\left[\frac{0.6P_1D^5}{\rho gfl}\right]^{1/2}-\left[\frac{0.48d^5}{\rho gfx}\right]^{1/2} \text{ in B/D} \quad 16$$

This is the modified darcy equation for leakage detection in oil pipelines.

3.1. DATA USED

P_1 = 500psia = 3377500 pa or Nm^{-2}, assumed.

15psia = 101.325kpa = 101325pa

D = 1219mm = 48inch = 1.219m. This is the diameter of the most frequently used pipeline in Nigeria[1]

ρ = density of gasoline = 711.22kgm^{-3} g = gravity = 9.8ms^{-2}

f = frictional factor = 0.0104, calculated using eq.(9).

The material of the pipe used is steel rusted. For steel rusted,

Roughness ε = 0.5mm (see moody chart)

The relative roughness $\varepsilon/d = \frac{0.5mm}{1219mm}$ = 0.4102

The reynold number is arbitrarily chosen to be in the turbulent region. Re ≥ 4000
Re = 5000 was chosen in this work.

The pipeline represented by eq. (16) is simulated using Matlab as follows;
(a)The variation of pipeline length (L) with flow rate at full capacity with internal diameter (d) of the leak kept at 0,ie no leak. The result is shown in Fig3.
(b)The thickness of the leak(x) is kept constant at 0.4mile and the leak diameter (d) is varied at pipeline lengths (L) of 10mile,20mile, and 30mile.The variation of flow rates with leak diameter is shown in Fig4.
(c)The length of the pipeline (L) is kept constant at 20mile and the leak thickness or preferably the inserted pipe/host length(x) is varied. The variation of flow rates with leak thickness at leak diameters of 10inch, 20inch, 30inch and 40inch is shown in Fig5.

4. RESULTS AND DISCUSSION

(a) The simulation results in Fig3 shows that as the length of pipeline increases, the gasoline flow rate decreases.
(b) Fig4 shows that as leak diameter increases, the flow rate decreases and this decrease is more pronounced as the pipeline length increases. The decrease in flow rates is highest for a pipeline length of 30miles and lowest for 10miles. Thus with leaks, the flow rate decreases proportionately.
(c)Fig5 shows a special case where oil (gasoline) leakage is by sabotage/theft otherwise called bunkering. It shows that if pipeline is opened, may be during downtime (or induced downtime due to sabotage) , and a long and wide host/pipe is inserted to tap oil, as the host length and leak diameter increases, the flow rate drops abruptly and immediately appreciates. The pipeline engineers may attribute such to pressure or flow surge or even operational faults when large quantities of Oil is being stolen from the pipeline. At smaller leak diameter of 10inch, there is little or no change in flow rates Fig.5. The control room pipeline operator may think that the leak is very small or may not notice any change in flow parameters at all. This is the major breakthrough in this work. Thus, when a large hole is made on a pipeline during down time and a long host is used to tap oil from the pipeline, the engineers in the control room may not know that a large volume of oil is being diverted, hence the need to be on alert when any of the flow parameter changes no matter how small. This is a validation of the previous work on gas pipeline using methane [23]

5. CONCLUSION

Pipeline control room engineers should not treat with levity any small change in flow parameters eg volume and mass flow rates, pressure changes etc. This is the major breakthrough in this work. If there is a sudden change in flow parameters and an instant appreciation, one should suspect a wide and long host/pipe forged on the pipeline. In Nigeria, this is done as a coordinated/organized sabotage.

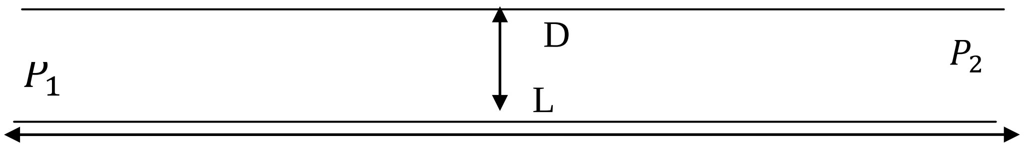

Fig1: Pipeline showing inlet and outlet pressure

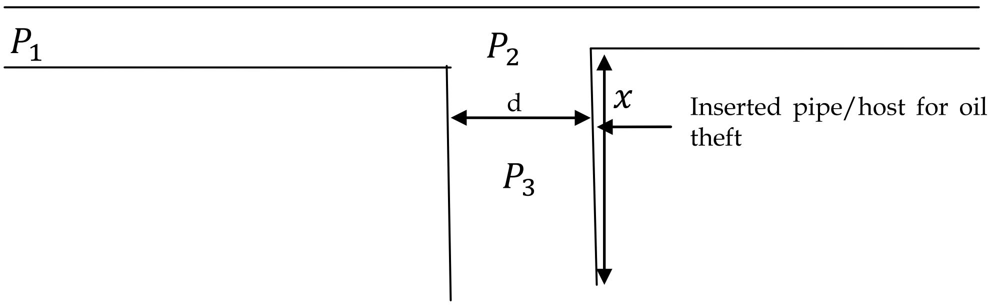

Fig2: pipeline showing a leak with thickness or inserted pipe length x and leak diameter d.

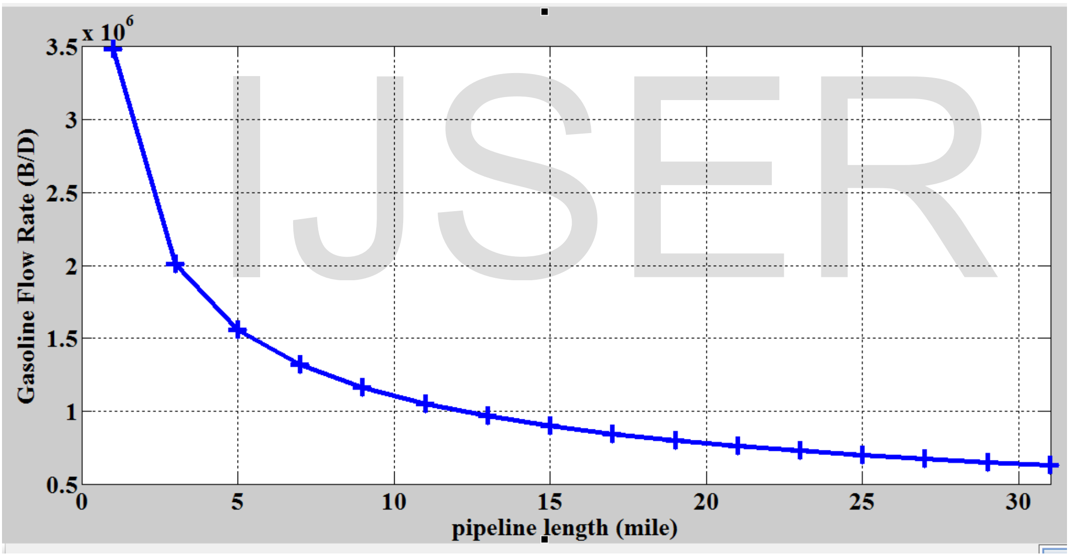

Fig3: Graph of gasoline flow rate(Q) vs pipeline length(L) at constant leak diameter(x)

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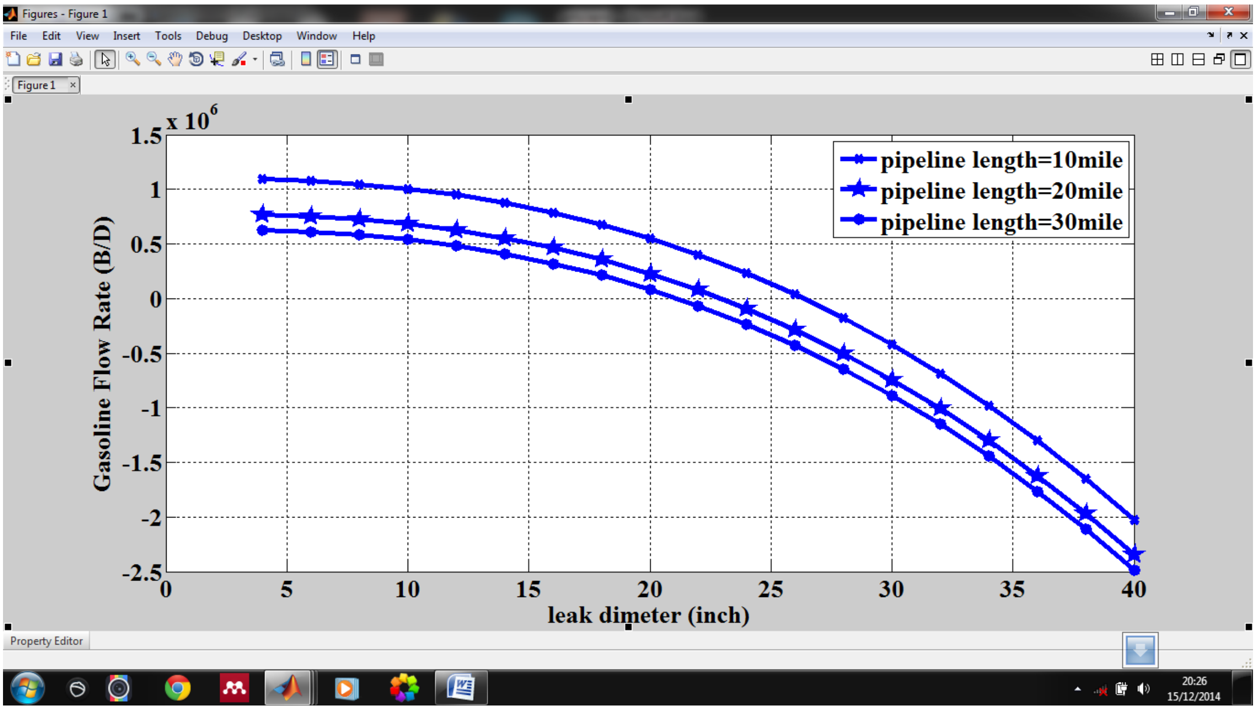

Fig4: Graph of gasoline flow rate(Q) vs leak diameter(d) for different pipeline lengths at constant leak thickness x =0.4mile.

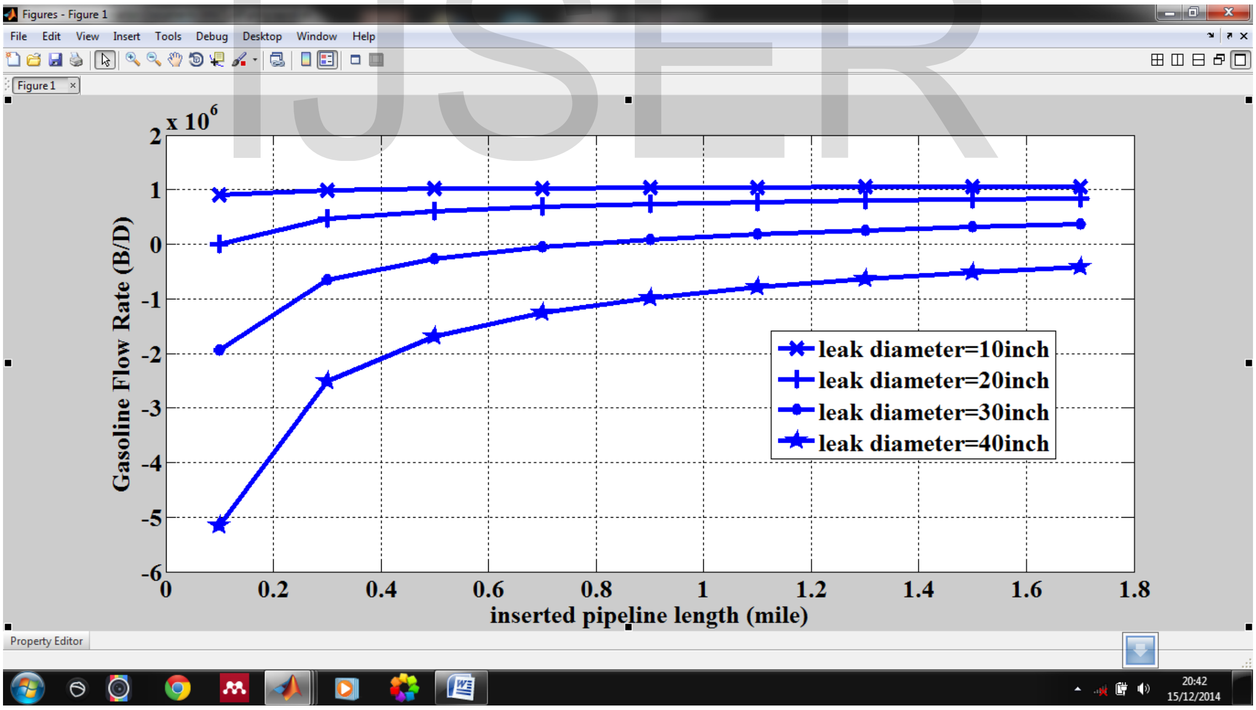

Fig5: Graph of gasoline flow rate (Q) vs inserted pipe length(x) for different leak diameters at constant pipeline length L = 20mil

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