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THE EFFECT OF THE INTERNAL SURFACE AGING IN THE TRANSMISSION EFFICIENCY OF A NATURAL GAS PIPELINE

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Abstract

The intent of this work is to evaluate the variations of the internal surface roughness in a natural gas pipeline along the years. A section of the GASBOL with 120 km and nominal diameter of 32 inches with internal coating delimited by two compressor stations have been analyzed during the period of 2005 and 2011. For internally coated pipes the corrosion is not the main mechanism that will promote degradation of the pipeline capacity. In this case, internal epoxy coating can be damage due to various pigging campaigns that are necessary to ensure pipeline's integrity. In order to determine whether or not pigging is affecting the transmission efficiency the effective roughness of the pipeline is calculated using an isothermal and steady state model. The results indicate that after various pig's runs there are no evidences that the marks left by the pig parts on the internal pipe surface have significantly impacted the flow characteristics of the pipeline. Moreover, the results indicate that the effective roughness has been reduced at rate of 0.29 μm/year, given that the absolute roughness of the pipeline is around 2-9 μm.

1. Introduction

Throughout the life cycle of a pipeline it is common to encounter changes in the transmission characteristics that affect the flow behavior of the natural gas. Those changes are essentially due to unexpected variations in temperature, gas composition and the amount of condensates or liquids in the pipeline as mentioned in Gregg et al. (2009).

Strupstad (2009) pointed out that a small amount of liquid in the natural gas could increase or decrease the pressure drop in a pipeline. This effect depends on the gas velocity and the liquid properties, for higher gas velocities the liquid tend to promote a smoothening of the internal surface and increase the pipeline capacity. On the other hand, there are other mechanisms, such as corrosion, erosion or precipitation of material that adheres to the inner surface of the duct that promote the deterioration of the pipe efficiency (Turner, 1991).

For internally uncoated pipes, the increase in internal roughness may occur at a rate of 0.76-1.27 μm/year, while for pipelines with coating, the rate of increase is in the range of 0.25-0.38 μm/year as found by Narsing and Golshan [in Abdolahi et al. (2007)]. However in Mohitpour et al. (2003) it has been mentioned that for coated pipes the rate of increase is between the ranges of 30-50 μm/year while for uncoated pipes these values are within the range of 50-75 μm/year. In Taghavi (2013) the typical roughness of uncoated pipes are within16.5-19.0μm and is increased at a rate of 0.76-1.27μm/year due to corrosion, erosion and other factors. In a pipeline transmission the increase in the internal roughness represents a serious problem as long as there is a direct impact on the transportation capacity. In Fournier and Kuper (1994) it has been reported that the roughness of the a natural gas pipeline has changed from 4 μm to more than 12μm in a period of 20 years with significant impact on the transport capacity. In the work of Woldeyohannes and Majid (2011) the authors evaluated the effect of the aging in a network of natural gas pipelines, taking into account the impact on flow capacity. The authors compare three different groups of pipelines, new, ten and twenty years old and conclude that the reduction is 2.16% for ten years and 4.53% for twenty years.

Sletfjerding et al. (1998) performed an experimental study to investigate the effect of the internal roughness on the transport capacity of natural gas pipelines at high Reynolds numbers. The authors pointed out that due to low

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viscosity and high density of the natural gas encountered in transmission pipelines the Reynolds number exceed the boundaries of the Colebrook-White correlation that is $1x10^6$. The experiments indicated the effective roughness of the coated pipe is 1μm while the steel pipe is 21 μm.

In Farshad et al. (2001) the results of measurements of the roughness in internally coated pipes are presented. The authors called attention to the fact that the Moody's pipe roughness chart did not represent coated pipes as long as the technology is relatively new. Moreover, the literature covering internally coated pipes is scarce. They presented an equation to estimate relative roughness of the coated pipes and stated that the equation is valid for new pipes as long as there is deterioration of the coating with the age.

These facts require a periodic check to revaluation of roughness values used for the various sections of the pipeline, which would result in an undesirable condition, especially if taken into account the reduction in transport capacity.

2. Internal coating

Generally, a pipeline integrity plan involves the inspection of the pipeline periodically with Pigs. In large diameter pipelines, the weight of the Pig may contribute substantially with the wear of the internal coating. The weight of the Pig increases with the pipeline's diameter and consequentially the friction of the Pig parts with the pipe's surface is higher. The damage produced by the Pigs are shown in the Figures 1 and 2. The disks shown in pictures are cuts performed in the upper section of the pipe. They are good samples of the internal surface of the pipeline and its degradation along the years. The time interval between the removals of the two disks is 5 years. In Figure 1, there are two visible scratches, identified by A and B that are associated with two Pig campaigns.

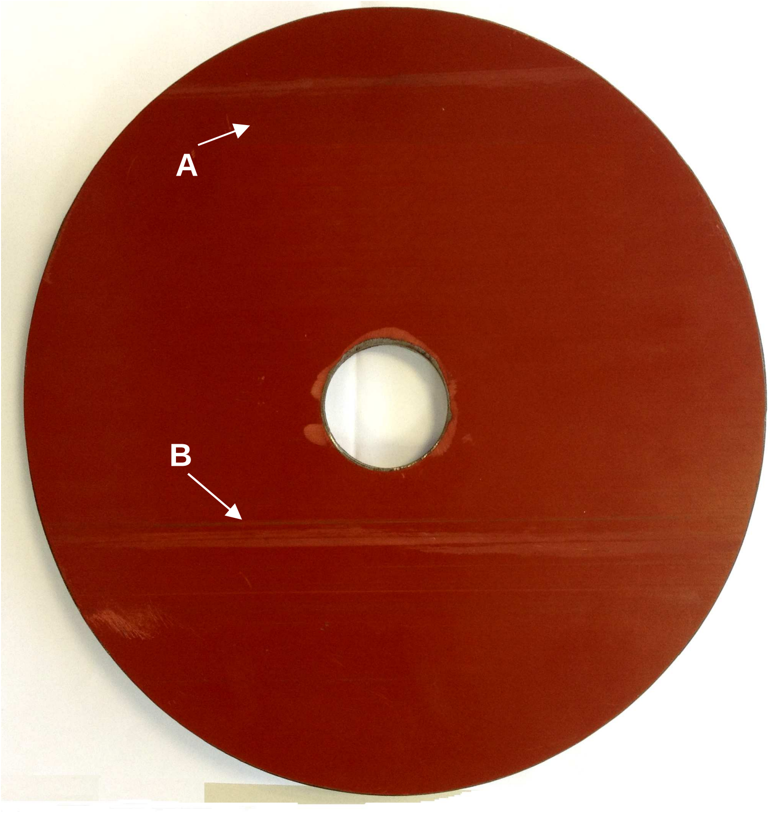

Figure 1– Scratches marks after two pigging campaigns.

In Figure 2, the disk cut was extracted from the pipeline five years later, after a third Pig campaign where the visible marks are identified by C, D and E.

Figure 2 – Scratches marks after three pigging campaigns.

In the Figure 3 an enlarged view of the scratches marks D and E of the Figure 2 provoked by the Pig friction is shown. A qualitative analysis of this picture demonstrates that the scratches produced by Pig friction with the coating causes the smoothing of the surface. Apparently, the differences between peak and valley of the surface have been reduced after Pig interference. Fournier and Kuper (1994) presented a work dedicated to estimate the effective roughness of the pipeline based on operational data. There is an interesting comparison of the results before and after pigging the pipeline. The data indicate that before pigging the effective roughness is around 24 µm and after is 5 µm, representing an increase of 8% in the transport capacity. Nevertheless, in the situation reported by the authors the mechanism that decrease the transport capacity is internal fouling.

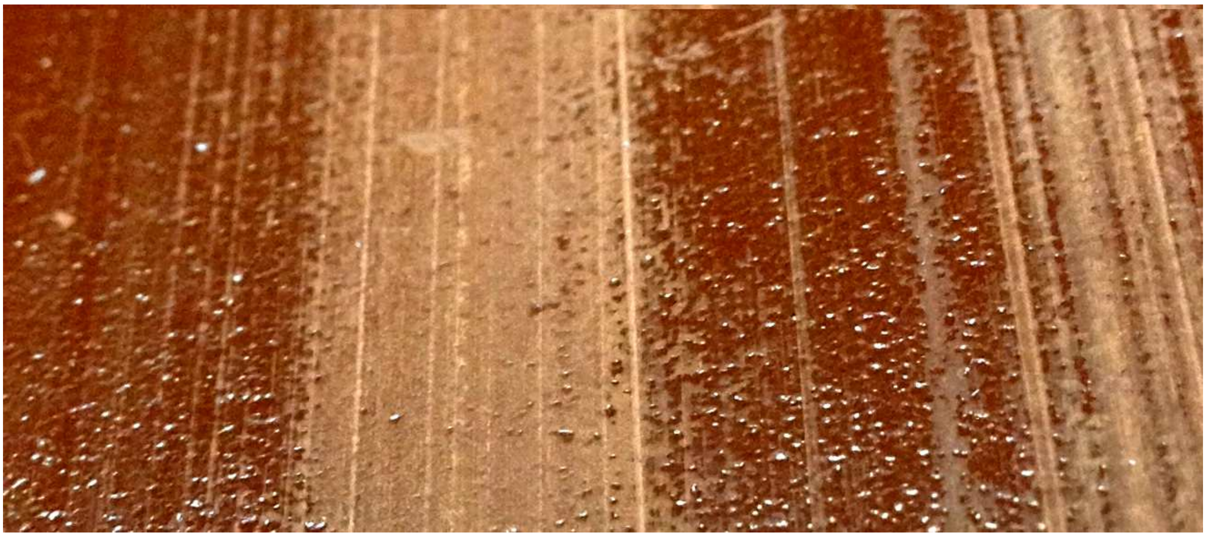

Figure 3 – Enlarged view of scratches marks D and E.

3. Friction factor

The friction factor is still subject discussed in several academic publications because it is the parameter that correlates various quantities of interest in fluid transport through pipelines. The friction factor is used to quantify the loss in pipes and thus finds application in a number of processes, not just limited to the oil and gas industry, but also the nuclear industry, automotive, aeronautics, etc.

In the work of Mikhailov (2000) is called attention to the existence of conceptual differences when using the traditional definition of roughness to calculate the friction factor. As noted, the traditional friction factor correlations were obtained with the roughness defined for a surface covered with grains of sand, while often the actual roughness of a pipe is significantly different of the idealized model. Thus, the author concludes that the introduction of a parameter in the Colebrook-White is needed to adapt such correlation to real situations.

In Romeo et al. (2002) is proposed an explicit correlation for the friction factor. The first part of the paper consists in a review of the most common explicit correlations available in the literature. After assessment, the best correlations are selected and three new models are proposed as a generalization or combination of correlations evaluated. The correlation is obtained for the range of Reynolds number from 3000 to 1.5 $x10^8$ with the error lower than 0.05%.

In the work of Langelandsvik et al. (2005) the effort is concentrated on getting the friction factor based on the operating conditions of a gas pipeline in operation. According to the authors there are no similar results in the literature for the calculation of the friction factor with the data presented, with flow in the transition region, and the Reynolds number in the range of $1x10^6$ to $5x10^6$, absolute roughness around 2.54 μm and diameters ranging from 30 to 45 in. The results lead to the conclusion that the Colebrook-White equation does not show satisfactory agreement with the operational data.

In Yang et al. (2005) it has been reported the ability of the Colebrook-White in determining the friction factor of a natural gas pipeline internally coated with epoxy. The results obtained by the correlation of Colebrook-White were compared with experimental data and operational data, indicating good agreement between them, for Reynolds number between 10^5 and 10^7.

In Veloso et al. (2007) it is proposed an explicit correlation for the friction factor derived from Colebrook-White and Lehmann for the range of Reynolds number from 10^3 to 10^6 and relative roughness 10^{-6} to 0.05. As reported by the authors, the Lehmann correlation is mainly used by German industry and differs from the Colebrook- White equation only because of the constants and exponents. Besides the proposed correlation, the authors compare 12 other correlations available in the literature, based on implicitly correlations and conclude that the proposed correlation has the lowest relative deviation.

In the study of Fang et al. (2011) two new correlations for the friction factor, one for smooth pipes and another suitable for smooth and rough pipes, both for fully turbulent flow are presented. The authors derived the correlations using a database generated with the Colebrook equation and the equation of Nikuradse, covering the range of Reynolds number from 3000 to 10^8, and the relative roughness of 0 to 0.05. Moreover, the authors present a study over 15 correlations compared with the Colebrook-White equation.

In Genic et al. (2011) a study involving 16 explicit correlations for the friction factor compared with the Colebrook-White equation is presented. The study covered the range of Reynolds numbers from 4000 to 10^8, and the relative roughness of 0 to 0.05. Among the correlations evaluated, the average percentage error was between 0.03% and 90.2%.

In Ghanbari et al. (2011) is proposed an explicit correlation for the friction factor based on scanned data from the Moody diagram for the range of Reynolds numbers 2100 to 10^8 and relative roughness from 0 to 0.05. The data were adjusted through an adjustment algorithm for non-linear curves. Moreover, other authors compared 9 models available in the literature, including the Colebrook-White equation and conclude that the proposed correlation has the highest correlation with the Moody diagram.

4. Approach

During the pipeline operational life the majority of time, it is operated under transient conditions. Variations in operating conditions are introduced by a wide range of situations, among the most significant it is possible to relate the variations arising from changes in consumer demand at the delivery points, failures in gas compression units, environmental conditions, etc. Thus, the condition of isothermal steady state is a rare but well desired situation under the mathematical point of view. This condition makes feasible the use of simplified mathematical models under certain circumstances. As mentioned in Borujerdi-Nouri (2009) the isothermal assumption is valid for the situation where the pipeline sections are long enough to ensure that the heat transfer occurs between the fluid and the walls of the duct.

According to Menon (2005) Eq. (1) defines the relationship between the pressure drop and flow rate for the isothermal flow in steady state is given by the equation known as General Equation of Flow:

$$Q = 1{,}1494.10^{-3}\left(\frac{T_b}{P_b}\right)\left[\frac{\left(P_1^2 - P_2^2 - WP_m^2\right)}{\gamma_g T_m L_e Z_m f}\right]^{0,5} D^{2,5} \tag{1}$$

Where: Q (m3/day) is the volumetric gas flow rate at standard conditions, f is the Darcy-Weisbach friction factor, Pb (101.325 kPa) is the pressure at standard conditions; Tb (293.15 K) is the temperature at standard condition, P_1 (kPa) is the upstream pressure, P_2 (kPa) is the downstream pressure; γ_g is the relative density of the gas, T_f (K) is the average gas temperature, Le (km) is equivalent duct length, Z is the compressibility factor of the gas, D (mm) is the inside diameter of the pipe, W is the potential energy term.

Having defined the steady state isothermal flow equation for gas transmission pipeline in terms of volumetric gas flow, it is necessary to rewrite Eq. (1) to allow the determination of the internal roughness of the pipe. Therefore, Eq. (2) can be defined in terms of the friction factor:

$$f = \left(\frac{1{,}1494.10^{-3}}{Q}\right)^2 \left(\frac{T_b}{P_b}\right)^2 \left[\frac{\left(P_e^2 - P_s^2 - WP_m^2\right)}{\gamma_g T_m L_e Z_m}\right].D^5 \tag{2}$$

The natural gas properties were defined according to AGA8 equation of state and Lee-Gonzales-Eakin for dynamic viscosity.

In order to evaluate the absolute roughness of the pipeline the Colebrook-White friction equation is utilized.

$$\frac{1}{\sqrt{f}} = -2.\log_{10}\left(\frac{2{,}51}{\mathrm{Re}.\sqrt{f}} + \frac{\varepsilon / d}{3{,}7}\right) \tag{3}$$

Taking this equation as a starting point it is possible to obtain an explicit expression for the absolute roughness having as variables the Reynolds number and the friction factor. According Genic et al. (2011) the Colebrook-White equation was obtained as a combination of the Nikuradse equation (to completely rough duct) and the Prandtl equation (for smooth duct) and is valid throughout the turbulent region, with the Reynolds number ranging from 4000 to 10^8 and the relative roughness from zero to 0.05 that suites the range of the operational data considered in this work. After mathematical manipulation it is possible to obtain an explicit expression for relative roughness (ε/d) based on the Colebrook-White equation, given by Eq. (4):

$$\frac{\varepsilon}{d} = \frac{0{,}0185}{f.\mathrm{Re}}\left(-502.\sqrt{f} + 200.f.\mathrm{Re}.\exp\left(\frac{-\ln(10)}{\sqrt{f}}\right)^{\frac{1}{2}}\right) \tag{4}$$

It should be mentioned that the roughness calculated by this method does not take into account some geometric complexities present along the entire length of the pipeline, such as valves, fittings, and bends. However, according to Mohitpour et al. (2003) the effective roughness in a natural gas transmission pipeline is composed by three portions; surface roughness, interfacial roughness and roughness due to bends, welds, fittings and valves. If the flow is fully turbulent and natural gas is dry the laminar sublayer is relatively thinner, then it is reasonable to assume that the only significant portion of the roughness is the one represented by internal surface.

Having defined an expression to calculate the absolute roughness taking into account, pressure, flow rate, temperature and geometrical information of the pipeline it is possible to compare the evolution of the roughness based on historical operational data. A section of the GASBOL with 120 km and nominal diameter of 32 in delimited by two compressor stations have been analyzed during the period of 2005 and 2011. Thus, it becomes possible to check the effect of degradation or alterations in the characteristics of the pipeline internal coating over the several years of operation.

The operational data used as input were acquired using a filter to remove large variations resulting from transient flow regime. The criterion of the data filter defines the data is valid if the difference between upstream and downstream flow at the ends of the pipe section is less than 5%.

Table 1 presents the summary of the operational data along the years, where the gas flow rate is at the standard condition (273.15 K and 101.325 kPa), gas pressure and temperature are the average between inlet and outlet. The symbols Φ and σ, are respectively, the mean and standard deviation.

Table 1 – Statistical summary of the input data along the years.

Year		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Flow rate (10^6 Sm³/d)	Φ	23.4	24.4	24.5	31.1	23.5	26.8	28.3
	σ	1.6	2.5	1.5	1.3	3.4	2.8	3.4
Pressure (MPa)	Φ	8.33	8.06	8.05	7.99	8.10	8.10	8.05
	σ	0.47	0.50	0.50	0.57	0.67	0.57	0.61
Temperature (K)	Φ	305.4	304.9	304.3	305.8	304.4	303.6	305.9
	σ	2.7	1.9	1.9	1.6	3.3	2.9	2.3

5. Results

This section presents the results based on a period of six years where the operational data were processed to result in the effective roughness. Figure 4 shows the absolute roughness calculated by the Colebrook-White correlation, grouped by flow rate ranging from 20 million m³/day to 30 million m³/day in the period from 2005 to 2011. Additionally, the average flow rate per year is shown and makes possible to identify whether there is a correlation between temporal variation of the roughness and flow regime. The dashed dark line is the average flow rate associated with the right hand axis

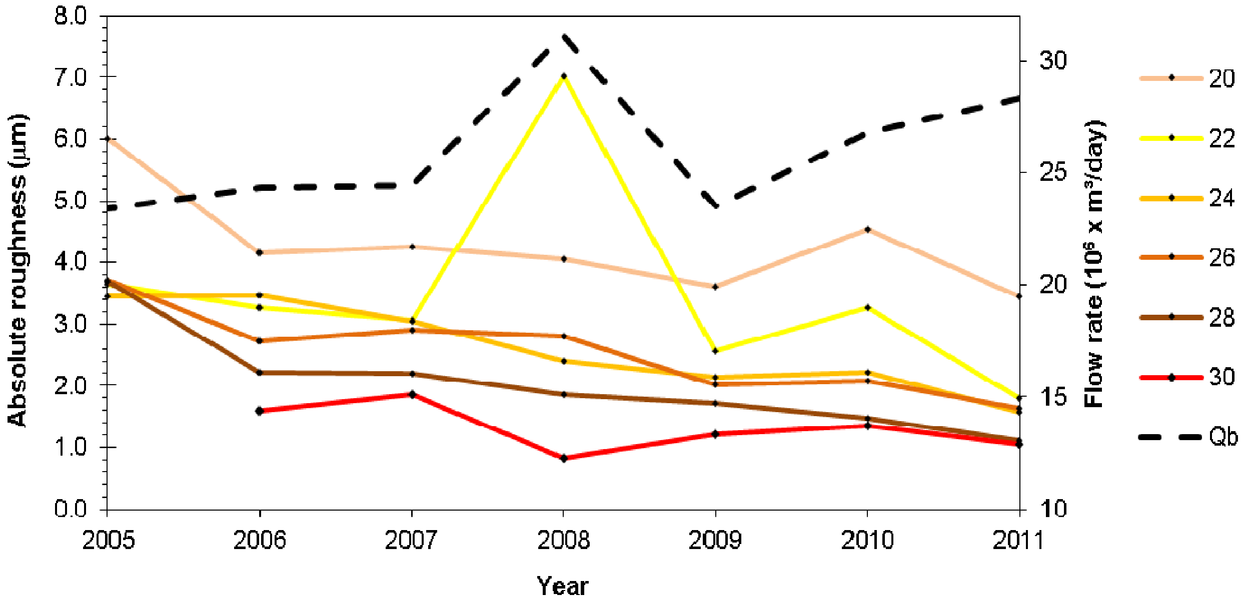

Figure 4 - Evolution of the absolute roughness and flow regimes per year.

The various curves shown in the graph suggests that there is a reduction in the effective roughness along the years. The reduction over time is verified for all flow rates, on the other hand, it may also be noted that the curves representing the lower flow levels are associated with higher values of surface roughness. In order to analyze more clearly the dependence of the roughness on the flow rate, Figure 5 has been included. In other words, this behavior represents the nonlinearity of the friction factor correlation, as long as the roughness should be independent of the flow rate.

In the Figure 5 it is possible to verify the dependence of the calculated roughness with the variation in the flow rate. The higher is the flow rate, the lower is the effective roughness. Such dependency is verified in any set of data independently of the year and an explanation for this behavior is associated with the nonlinearity of the correlation to calculate the friction factor.

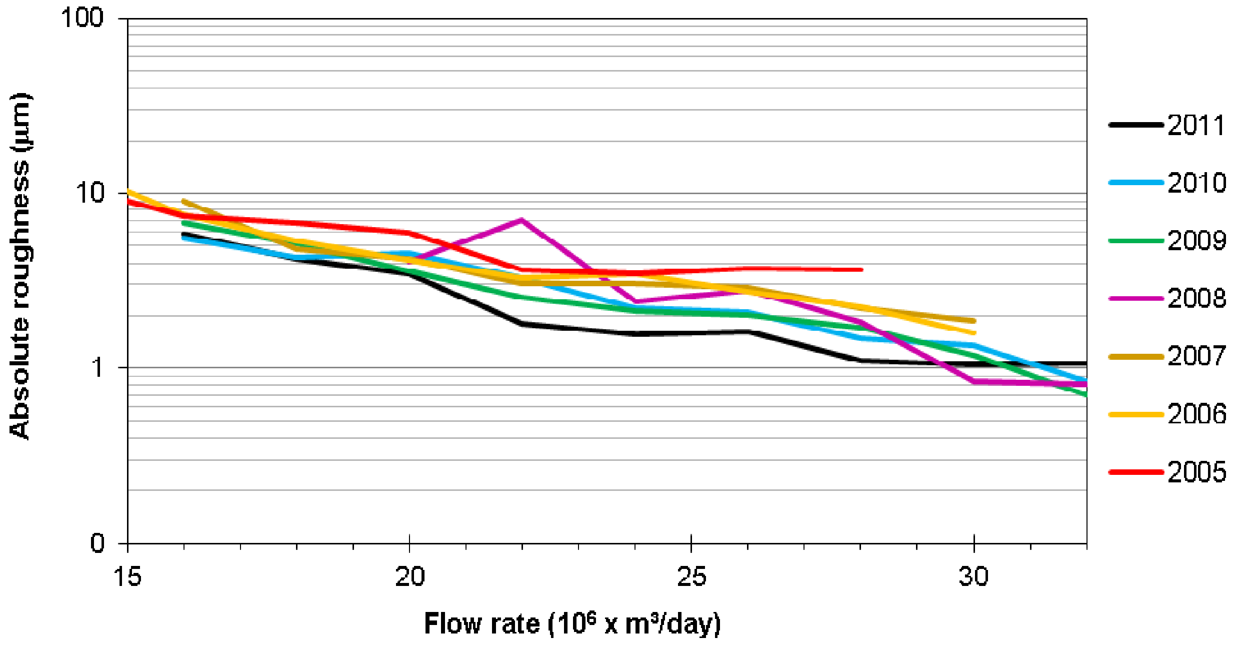

Figure 5 – Calculated absolute roughness along the years.

Based on the results presented in Figure 5, the average roughness is calculated during the interval 2005-2011 and the results are shown in the Figure 6 (yellow dots). The dashed red line is a curve adjusted by power-law model that represents the dependence of the roughness on the flow rate. In practical terms the equation presented in the Figure 6 is useful to overcome the deficiency of the friction factor to correlate flow and pressure drop in the pipeline linearly. Depending on the range of the flow rate that the pipeline is operating it is necessary to a different value of the roughness defined in the numerical model that simulates the gas flow.

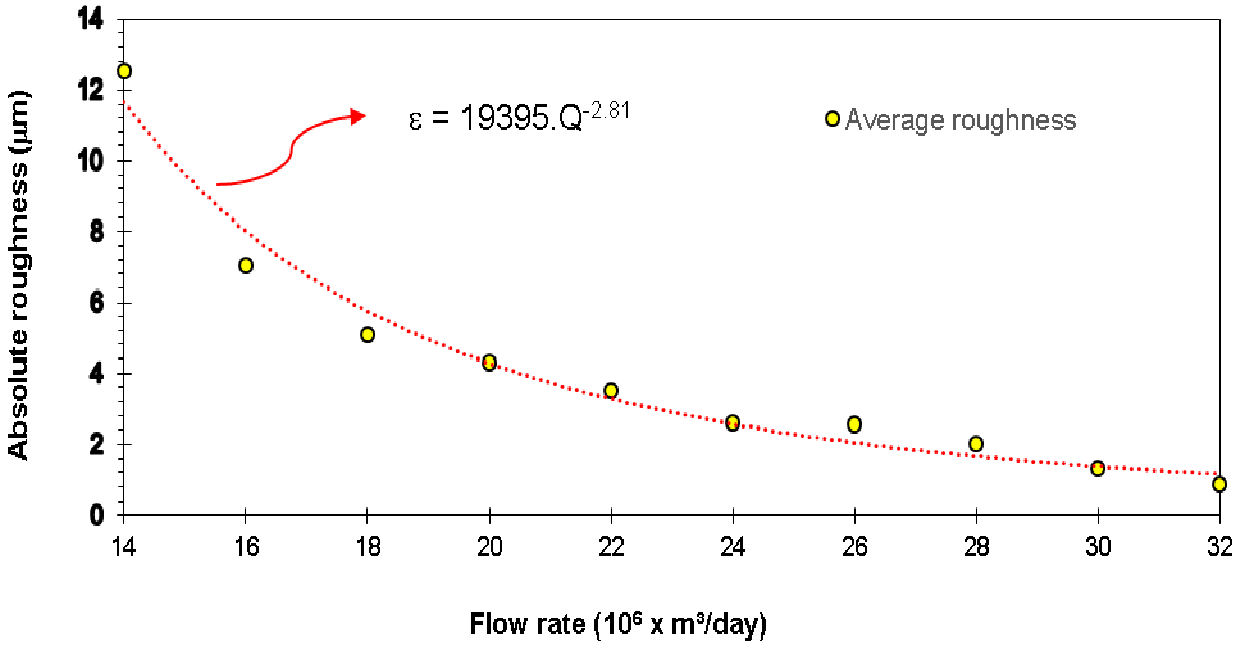

Figure 6 – Average roughness versus flow rate.

Table 2 presents the parameters (Reynolds number and friction factor) obtained from the operational data along the years, while the absolute roughness is the average per year. The absolute value of the roughness is within the range of 4.1 and 1.9 µm, which are in agreement with the results reported by Fournier and Kuper (1994) and Farshad et al. (2001) for coated pipes.

Table 2 – Statistical summary of the calculated data along the years.

Year		**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Reynolds (10^6)	Φ	23.5	24.6	24.8	31.1	23.9	27	28.4
	σ	0.16	0.24	0.15	0.14	0.35	0.28	0.34
Friction factor	Φ	0.0079	0.0079	0.0078	0.0072	0.0078	0.0076	0.0073
	σ	0.0003	0.0003	0.0002	0.0002	0.0004	0.0003	0.0003
Absolute Roughness (µm)	Φ	4.1	3.17	3.09	3.63	2.41	2.71	1.91

The trend in terms of the variation in the roughness along the years is shown in the Figure 7, where the roughness per year is calculated excluding the boundaries of the data set, in other words, the results exclude the flow rate lower than 18.10^6 m³/day and higher than 28.10^6m³/day.

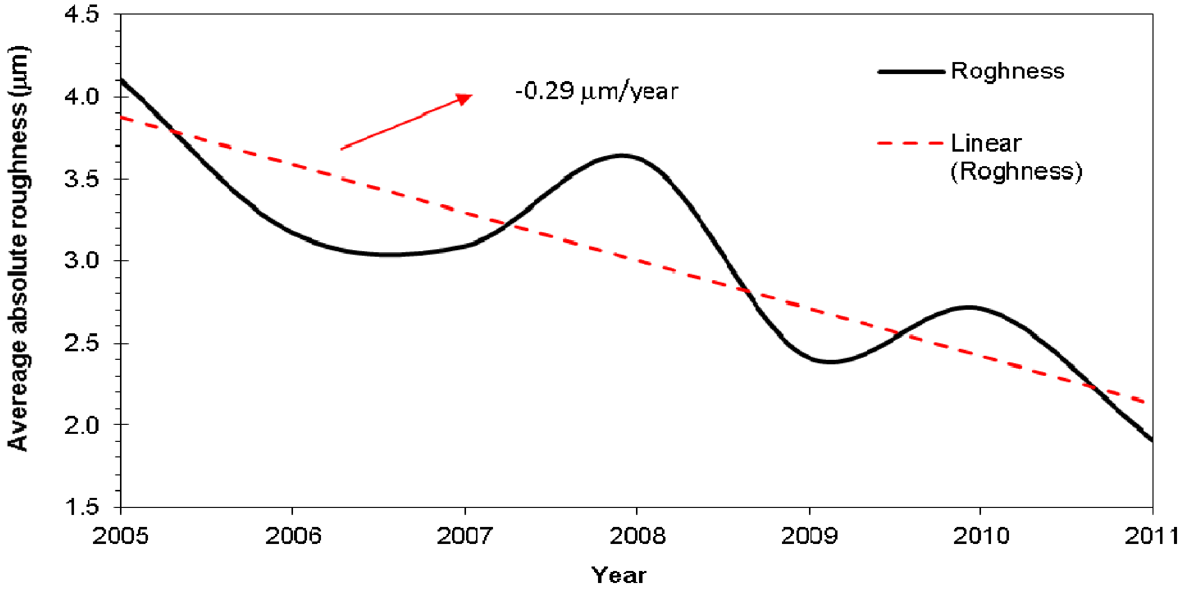

Figure 7 – Evolution of the calculated absolute roughness along the years.

6. Discussion and conclusion

Based on the average roughness calculated over the years it is possible to identify a clear trend in the behavior of the effective roughness, indicating that the roughness has been reduced at rate of 0.29µm/year. Although, there is a reduction in the effective roughness verified over the years the critical evaluation of the results reveals that flow regime of the pipeline has an important influence. Thus, some aspects that should be taken into account before assuming that the effective roughness is decreasing. The causes of the reduction in the effective roughness may be associated with the following factors:

- Degradation of the measurement, specially the errors of the flow meters;
- Deviations of the correlation to estimate the friction factor;
- Changes in the operational profiles of the pipeline;
- Procedure to filter transient portions of the input data;
- Simplifications assumed into the modeling (steady-state, isothermal and one-dimensional);
- Environmental variations (ambient temperature).

After all, even considering these factors, the results make clear that the damage caused by pigging do not reduce the capacity of the pipeline, or in a more conservative perspective are negligible.

8. References

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