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Mathematical modeling of fluid motion in pipelines using drag reducing agents

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ABSTRACT

One of the methods currently used to increase pipeline transfer capacity, when the option of extra loops or pumping stations is unavailable, is the use of the drag-reducing agents (DRA).

DRA are long-chain polymeric compounds that reduce turbulent frictional losses. Nowadays there is no complete theory that explains this phenomenon, known as the Toms effect. In the course of the DRA flow in a pipeline the efficiency of the turbulence suppression decreases, most likely due to breakup of the long molecular chains into shorter ones.

In this paper a mathematical model of viscous liquid motion containing DRA is proposed. The model takes into account the gradual breakup of DRA in a pipeline flow. The influence of DRA is considered as a dependence of hydraulic resistance coefficient on the DRA concentration; the DRA concentration in turn depends on a travel distance in a pipeline.

DRA

One of the methods of solving this problem is to use drag reducing agents (DRA) – special additives to oil and oil products. DRA reduce hydraulic resistance through suppression of turbulence along the pipeline walls. Using DRA helps to avoid installing new pumps, building extra loops, pumping stations, etc.

DRA are long-chain molecules with certain solubility in the transported oil. DRA are injected in the pipeline in extremely low concentration – several grams per tonne, providing the decrease of hydraulic resistance by 30%-50%. More than that, it was experimentally shown that there exists a certain limiting concentration for each type of DRA. The increase of DRA concentration above these limits will not result in significant improvement of DRA efficiency (See Figure 1).

Usually, DRA are injected in the pipeline immediately after pressure control valves in the pumping station. It is due to the fact that in the motionless solution polymeric molecules are rolled in weakly symmetrical coils, saturated by dissolvent. In the area of strong turbulence downstream of the pumps molecular coils unroll. While unrolling, DRA molecules absorb part of the turbulent energy, and after they unroll completely they prevent further progress of stream perturbations, decrease their length and reduce the occurrence of new perturbations.

This effect is named after British scientist Toms, who discovered it by chance in 1948. The effect is related to dissipation of turbulence due to the decrease of the cross velocity pulsations caused by the additives. The crucial characteristics of the polymer that determine the hydraulic efficiency of the DRA are heavy molecular weight, and elongated asymmetrical construction of the molecules. Chain-length distribution (CLD) affects the polymer resistance to breakup. The efficiency of the polymer is mainly determined by the heaviest molecular fraction. In polymers with wide CLD the fraction of the big macromolecules is small, so the polymers quickly degrade and DRA loose efficiency. For the DRA with the same breakup speed but with narrower CLD the duration of polymer activity is considerably longer. Consequently, it is preferrable to use polymer patterns with heavy molecular weight and narrow CLD to achieve the best efficiency of DRA (minimal destruction, maximal decrease of the resistance).

The use of DRA provides effective and economic operation of the pipeline in the following cases:

- Use of the pipes with larger diameter is complicated in consequence of the geographical conditions and other properties of the environment (for example sea pipelines, or pipelines in tropical or arctic regions);
- For the temporary increase of the pipeline capacity to accommodate peak flow levels;
- Building more pipeline capacity is not feasible;

- Pipeline is operated in zone of maximum possible pressure. Additives allow operating pipeline at higher capacity without pressure increase;
- There are restrictions on the pump capacity. With DRA the pipeline is able to operate at higher capacity on the same pumps.

Ideally, for the sake of efficiency DRA should dissolve in the transported fluid and be resistant to breakup in a turbulent flow. In fact the efficiency of DRA decreases while moving down a pipeline because of the breakup of large molecules. Polymer destruction in the turbulent flow is a serious problem due to close relation between hydraulic resistance decrease effect and polymer molecular weight. Polymer destruction during the flow can occur 1) at the beginning of the pipeline; 2)in the mid-flow due to the long stay in turbulent shearing field; 3) at the end of the pipeline (vertical turbulent effect). The first and the third factors are typically less important then the prevalent second factor.

Factors that affect operational characteristics of DRA are:

- Presence of turbulence, otherwise, in a laminar flow, DRA are useless;
- Viscosity (the lower is viscosity, the more efficient are DRA). The influence of viscosity depends on the flow regime. If the viscosity is quite high, the pipeline simply does not move from laminar to turbulent regime;
- Temperature (the higher the temperature, the lower the viscosity and the higher the solubility of the additives). With temperature increase the onset of the Toms effect shifts to higher Reynolds numbers.
- Inner diameter. This is related both with the decrease of the ratio of the wetted perimeter and sectional area of the pipeline (the effect occurs in the boundary area) and with the decrease of the shear stress on the pipeline walls;
- The fraction of water or paraffin in the oil. High fraction of water or paraffin reduces the efficiency of DRA.

In temperature range 0ºC - 50ºC (32F - 122F) the DRA efficiency varies by approximately 10%. Polymeric DRA are more efficient in low-viscosity oils, but the use of DRA is worthwhile in oils with viscosity 15-20 cSt.

According to experimental data, additives do not change crucial properties of the transported fluids. Injecting DRA Necadd-547 in diesel oil caused a drop only in one fluid parameter – filterability. It was established that after DRA-enriched oil had passed through the pumps, i.e. after the destruction of polymeric molecules, the filterability did not differ from the normal value.

Nowadays the most adequate model to describe the flow of the fluid with DRA is so-called model with fluctuating layer (Prandtl model). During the flow of fluid with DRA viscoelastic “drops” of polymer (they are 3-4 times bigger than the molecules of dissolvent) drift to the pipeline walls, where a layer of a hydrodinamically active polymer is formed. Unlike absorptive layer, the fluctuating layer is a component of the moving volume of the fluid.

During the formation of the fluctuating layer the concentration of the polymer in the volume of flowing liquid decreases. At the same time this concentration increases in the boundary area. The increase of polymer concentration in boundary layer causes fluid to show characteristic viscoelastic properties which are related with the turbulence suppression.

In a boundary layer of the turbulent flow molecules undergo random actions of vorticity and deformations. Steady motion is interrupted by intensive surges of impeded fluid near the wall in the external area of boundary layer. Turbulent surges are drowned streams, these streams axial motion is motion with shear. At certain shear rates of a flow molecular coils unroll, and after unrolling they prevent further appearance of the surges.

A model with a fluctuating layer allows to explain many available experimental data. The strong dependence of hydraulic resistance decrease on DRA concentration (See Figure.1) is interpreted that this fluctuating boundary layer has certain size and after it is filled, the maximal efficiency of DRA is reached.

This theoretical model also allows to explain the influence of the polymeric molecular weight on the DRA efficiency. A polymer molecule must be of a certain minimal size, otherwise fluctuating layer will not be formed. Therefore DRA efficiency increases with increasing of the molecular weight of the polymer. But this process has limitations. As soon as macromolecule’s size exceeds certain optimal value, spheres of influence of different molecules start overlapping, and there is no significant improvement of fluctuating layer formation.

Thereby, DRA affect turbulence mostly in the boundary layer, specifically in its transition zone. The transition zone is between the turbulent core and laminar boundary layer of the flow. In transition zone molecular viscosity and turbulent effects are equally important. The presence of macromolecules results in dissipation of high-frequency pulsations, decrease of the molecular viscosity and increase of the thickness of the laminar boundary layer. Beyond ~~of~~ the viscous layer there prevail large-scaled vortices of inertial origin and there is practically no DRA influence in the point of turbulence suppression.

At present there is no unified theory that allows one to quantify the change of the DRA influence as additives move down a pipeline. We only know that in the process of moving down a pipeline efficiency of turbulence suppression falls, presumably due to the breakup of long molecules into shorter ones. Suppression of turbulence is likely the result of destroying long molecules of polymer additives. It is known that when the oil flows through pipeline forks, sharp turns, restrictions and other obstacles of different kind (such pipeline places can initialize the formation of a vortex flow), the efficiency of the additive decreases. After passing a centrifugal pump, where turbulence is very high, the efficiency of all known additives drops to zero and, if it is necessary to reduce the flow resistance of the next pipeline section after the pumping station, one has to re-inject DRA after the pumps.

It should be noted that the breakup of the additive only occurs after the dissolution of the commodity form in the flow of oil or oil products in which it is injected. Commodity forms of different manufacturers have different dissolution time, from several minutes to several hours. Additives that have long dissolution time may be ineffective in short pipelines and effective enough for relatively long. On the other hand undissolved additive is less prone to breakup even at such a significant turbulence, which occurs in centrifugal pumps, and this property may allow to inject DRA into the stream directly before the pumps, where due to the low pressure injection conditions are much simpler and more reliable, and therefore additive injection can be operated with the use of a simpler and cheaper equipment. Thus, the dissolution (activation) time of the additive is also its important characteristic.

DRA affect all the processes in the pipeline therefore obtaining a relation that allows taking DRA influence into account is a matter of interest. The presence of DRA is an important factor both for the computation of common processes (steady-state regimes, switching of the pumps, etc.) in the pipeline and the processes that are caused only by DRA. Such processes are processes of distribution of the DRA in the pipeline after beginning of the injection and removing of the DRA after stop of the injection.

MODELING

Modeling of the steady-state regimes of pipeline flow is usually relatively simple. Generally, classical continuity equation and momentum conservation equation are assumed as basis. Being supplemented with geometrical properties of a pipeline and specified boundary conditions, these equations give a complete picture of the flow motion. This differential equation system is solved by the method of characteristics. As a solution one obtains distribution of flow pressures and velocities along the pipeline.

Modeling of transient regimes of flow motion is more complicated. An initial condition (in addition to geometrical properties of the pipeline and boundary conditions in case of steady-state regime) is needed. This is an initial distribution of the parameters of the flow in a pipeline. This regime is a certain starting position for the next modeling. Usually some steady-state regime, calculated by Bernoulli equation, is taken as such initial condition.

Differential equation system used for computation of flow motion in the pipeline:

$$\begin{gathered}\frac{\partial p}{\partial t}+\rho c^2\frac{\partial u}{\partial x}=0,\\ \frac{\partial u}{\partial t}+\frac{1}{\rho}\frac{\partial p}{\partial x}+\lambda\frac{u\cdot|u|}{2\cdot D}+g\sin\gamma=0\end{gathered} \tag{1}$$

where p – pressure;
c – sound speed in a pipeline;
ρ – oil density;
u – flow velocity;
λ – hydraulic resistance coefficient;
γ – angle of the slope of a pipeline;
x – distance in a pipeline;
D – inner diameter of a pipeline.

For studying processes related to DRA, this model must be supplemented by a section that allows to calculate hydraulic resistance coefficient taking into account DRA's efficiency. Further the technique of identification how hydraulic resistance coefficient varies along the pipeline and relation between DRA's efficiency and hydraulic resistance will be examined.

Dependence of hydraulic resistance coefficient on distance travelled by DRA in the pipeline

As it was said before, most noticeably DRA influence affects the hydraulic resistance coefficient. So it is logical to examine the character of DRA destruction as a dependence of hydraulic resistance coefficient on current coordinate of the pipeline.

Identification of hydraulic resistance coefficient λ was done using the following formula:

$$P_1-P_2+\rho g(H_1-H_2)=\lambda\frac{L\rho u^2}{2D} \tag{2}$$

where P_1, P_2 and H_1, H_2– pressures and heights at the beginning and at the end of a pipeline respectively;
ρ– oil density;
L– length of pipeline section;
u – flow velocity;
D – pipeline inner diameter;

The dependence of hydraulic efficiency on distance travelled by DRA is built along the full length of pipeline section, filled with DRA. Coordinates of plot points in X-direction were determined the following way: examined section of the pipeline was divided into smaller (about 20-30 km, 12.4 – 18.6 miles) sections in succession, for each small section λ was calculated, each λ was assigned the coordinate of the midpoint of this section.

Such choice of points is associated with necessity to reduce errors, that are high enough in case of λ computation for pipeline section between adjacent pressure sensors (distance between them can be rather small, as low as 5 km, or 3.1 miles). At the same time, further length increase of the examined sections would result in sufficient decrease of the quantity of experimental points that would not allow to obtain a distinguished plot. Also when sections for hydraulic resistance coefficient calculation are chosen, it is necessary to exclude sections with close values of pressure and head at the beginning and at the end, because this considerably increases errors.

Dependence of DRA efficiency on distance travelled in the pipeline

Hydraulic efficiency of DRA is usually estimated as a relative decrease of hydraulic resistance coefficient of the pipeline, i.e.

$$\varphi(x)=\frac{\lambda_0-\lambda_{DRA}(x)}{\lambda_0}\cdot 100\%\,, \qquad (3)$$

where φ –DRA efficiency;
λ_0 – hydraulic resistance coefficient without DRA in pipeline;
λ_{DRA} –hydraulic resistance coefficient with DRA in pipeline;
x – distance in a pipeline.

If there is opportunity to obtain experimental data to calculate resistance in pipeline without DRA on the same small sections where it was calculated with DRA, it is better to calculate λ_0 for each small section, so $\lambda_0$will be a function of a travelled distance. If there is no such opportunity (one can not obtain data about commodity without DRA) to estimate hydraulic resistance in the pipeline with the same flow rate without DRA can be used Blazius formula

$$\lambda_0=\frac{0.3164}{\sqrt[4]{\mathrm{Re}}}\,, \qquad (4)$$

where Re – Reynolds number.

Naturally, Blazius λ_0 estimation yields to direct identification in respect of accuracy. Firstly because Blazius formula is empirical and owing to thes has its own errors and secondly hydraulic resistance can alter in the different sections of the pipeline under local properties (different wall thickness, different pressure losses on the valves).

Using (4), one can find DRA efficiency on each examined pipeline section and draw a corresponding plot.

Significance of DRA efficiency change for modeling

One of the principal equations of flow motion is momentum conservation equation already named above.

$$\frac{\partial u}{\partial t}+\frac{1}{\rho}\frac{\partial p}{\partial x}+\lambda(x)\frac{u\cdot|u|}{2\cdot D}+g\sin\gamma=0, \qquad (5)$$

In this equation the term $\lambda\frac{u\cdot|u|}{2\cdot D}$ stands for the hydraulic losses in the pipeline. Using (3) one can obtain the following equation

$$\lambda(x)=\lambda_0\left(1-\frac{\varphi(x)}{100}\right) \qquad (6)$$

Substitution of (6) into (5) allows taking DRA influence on flow motion into account in process of modeling.

Expiremental results

This section will examine the processes of oil transport with DRA in three pipelines with different fluids, inner diameters and capacities.

Pipeline#1 (See Figure 2)

Oil pipeline, inner diameter 0.5 m (19.69 inches), density 845 kg/m^3(7.05575 Ib/gal), viscosity 9 cSt, oil flow 1580 m^3/h (6957 gal/min), flow velocity 2.2 m/s (4.92 miles/hour), Reynolds number 123900.

Figures 3 and 4 show the dependence of the hydraulic resistance on distance traveled by DRA in the Pipeline I.

Analyzing data from graphs, we can conclude that they are reasonably well approximated by a simple linear dependence
$y=-0.14x+30.06$ for the section between pumping station-1 and pumping station-2
$y=-0.15x+35.37$ for the section between pumping station-2 and pumping station-3
(distance x is in kilometers).

Free coefficient (i.e, the initial efficiency) varies as there are different rates of additives on the PS-1 and PS-2.

Figures 5 and 6 show the dependence of the DRA efficiency on the distance in the pipeline I.

The coefficients of slope of efficiency are almost the same at both sites, i.e. breakup of the additives in these sections occurs with the same speed and is virtually independent of the initial efficiency.

Pipeline#2 (See Figure 3)

Diesel pipeline, inner diameter 0.5 m (19.69 inches), density 850 kg/m^3(7.0975 Ib/gal), viscosity 3 cSt, flow 1050 m^3/h (4623 gal/min), flow velocity 1.5 m/s (3.36 miles/hour), Reynolds number 248600.

Figures 3 and 4 show the dependence of the hydraulic resistance on distance traveled by DRA in the Pipeline II.

Figures 5 and 6 show the dependence of the DRA efficiency on the distance in the pipeline II.

Dependence of the DRA efficiency on the distance is approximated by a hyperbolic dependence of the form
$y = C / x^{\alpha}$, where C, α - constants.

Pipeline#3 (See Figure 4)

Oil pipeline, inner diameter 1 m (39.38 inches), density850 kg/m3(7.0975 Ib/gal), viscosity 9 cSt, oil flow 3600 m3/h (15850 gal/min), flow velocity 1.27 m/s (2.84 miles/hour), Reynolds number 141500.

Figures 3 and 4 show the dependence of the hydraulic resistance on distance traveled by DRA in the Pipeline III.

Figures 5 and 6 show the dependence of the DRA efficiency on the distance in the pipeline III.

Dependence is approximated by the function $y=C\exp^{\alpha}$, the constant C in this case is some ideal peak efficiency of the additive on this pipeline.

ANALYSIS OF RESULTS AND CONCLUSIONS

In all considered pipelines one can observe that DRA efficiency reduces as DRA move down a pipeline. The most common hypothesis is that this process is caused by mechanical breakup of the DRA polymer chains. This hypothesis is largely based on observations from the field of polymer chemistry, from which it follows that the effect of decrease of resistance strongly depends on the molecular weight of the polymer.

Regardless of the mechanism of this process, the efficiency of DRA decreases as DRA move down a pipeline, respectively, increases the coefficient of hydraulic resistance.

We can assume that the linear dependence of the efficiency on the distance in the Pipeline-I is associated with a small (compared to the Pipelines II and III) length of sections, where oil transports with DRA. Perhaps in case of increasing the length of this section dependence of the efficiency on the distance in the Pipeline-I will become exponential as well as in the Pipeline III.

In general, for the sake of modeling accuracy, the best option is the identification of the empirical dependence of the efficiency of DRA on traveled distance in the pipeline, because this dependence can vary considerably for different pipelines as well as for different types of DRA for the same pipe.

Biographies of the authors

Svetlana Strelnikova is an engineer at Energoavtomatika Ltd., Moscow, Russia. She has five years experience in working with real-time systems of mathematical modeling of fluid motion in pipelines. She is a third-year postgraduate student at Moscow Institute of Physics and Technology.

Diana Michkova is an engineer at Energoavtomatika Ltd., Moscow, Russia. She has three years experience in working with leak detection systems, based on physical measurements. She is a first-year postgraduate student at Moscow Institute of Physics and Technology.

FIGURES

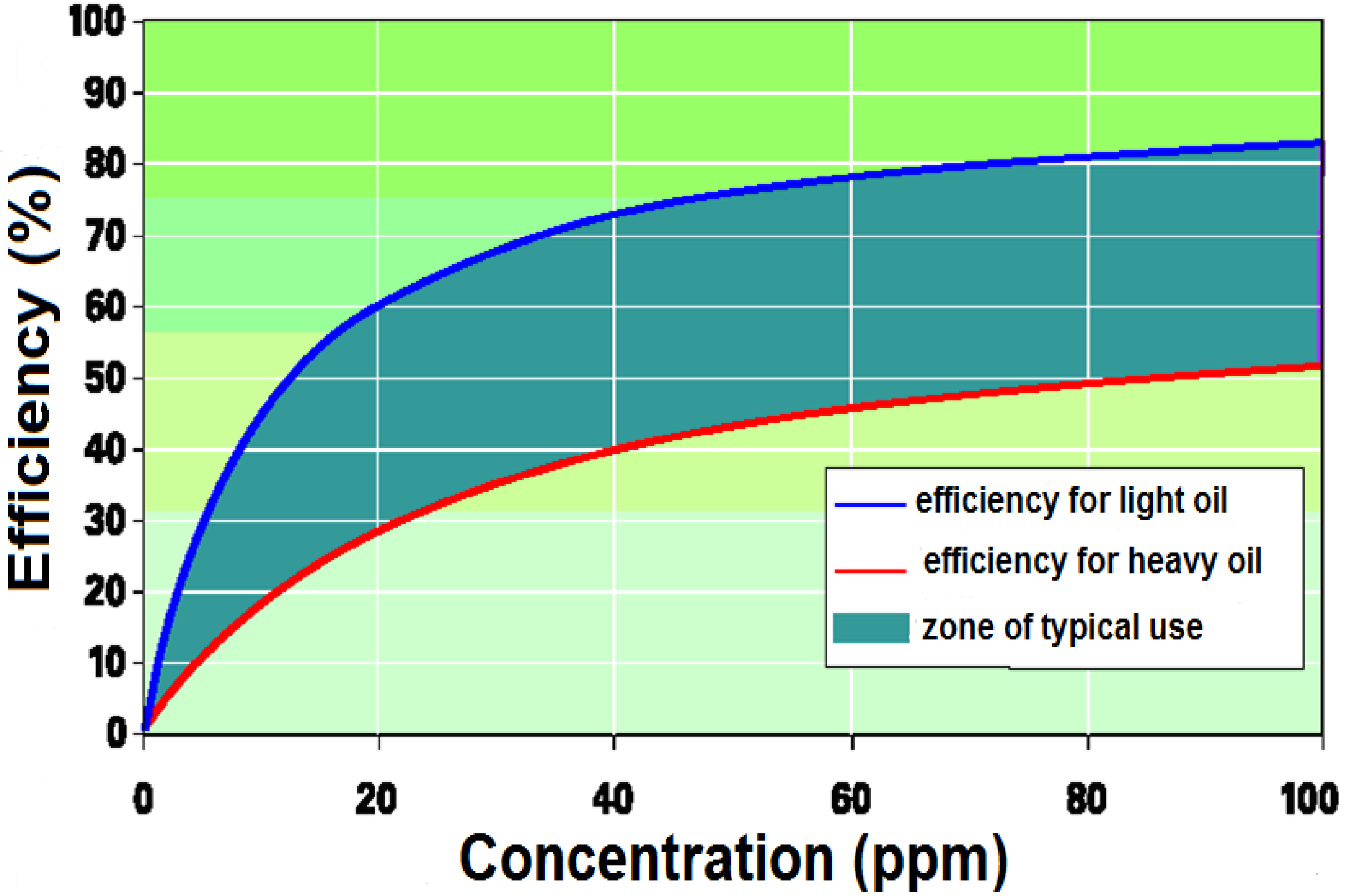

Figure 1 Typical relation of DRA efficiency on concentration

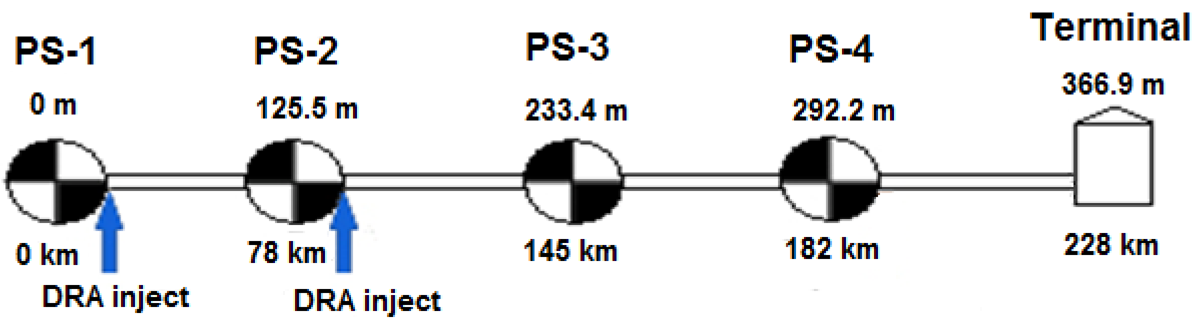

Figure 2 Scheme of the Pipeline#1

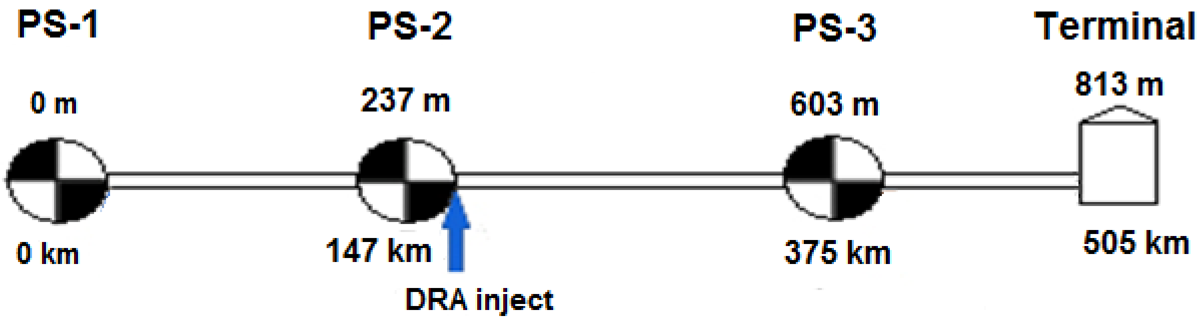

Figure 3 Scheme of the Pipeline#2

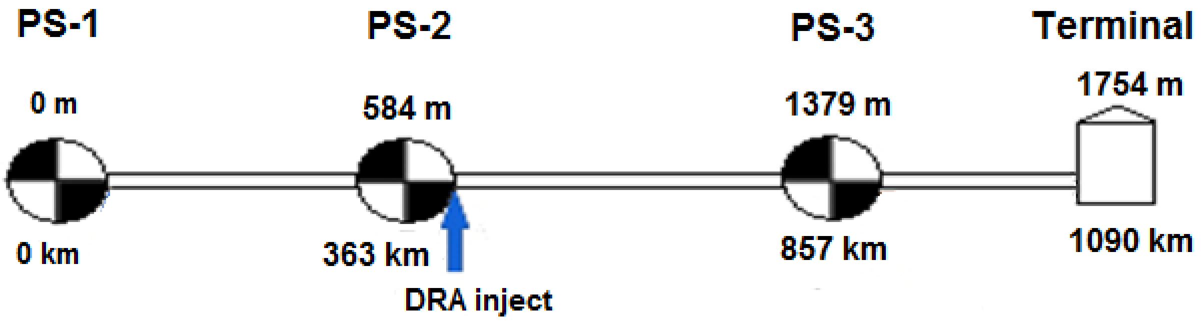

Figure 4 Scheme of the Pipeline#3

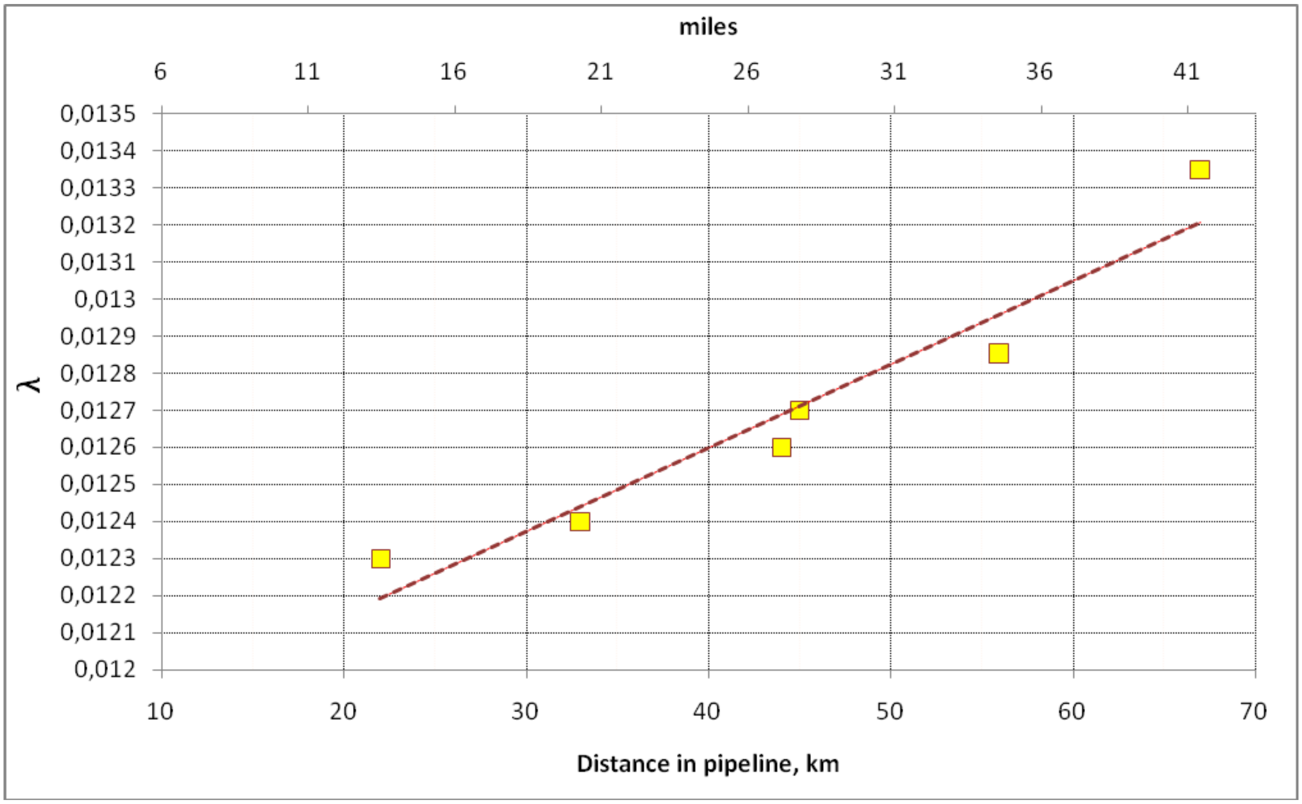

Figure 5 Dependence of hydraulic resistance on distance travelled by DRA in Pipeline#1 PS-1 – PS-2

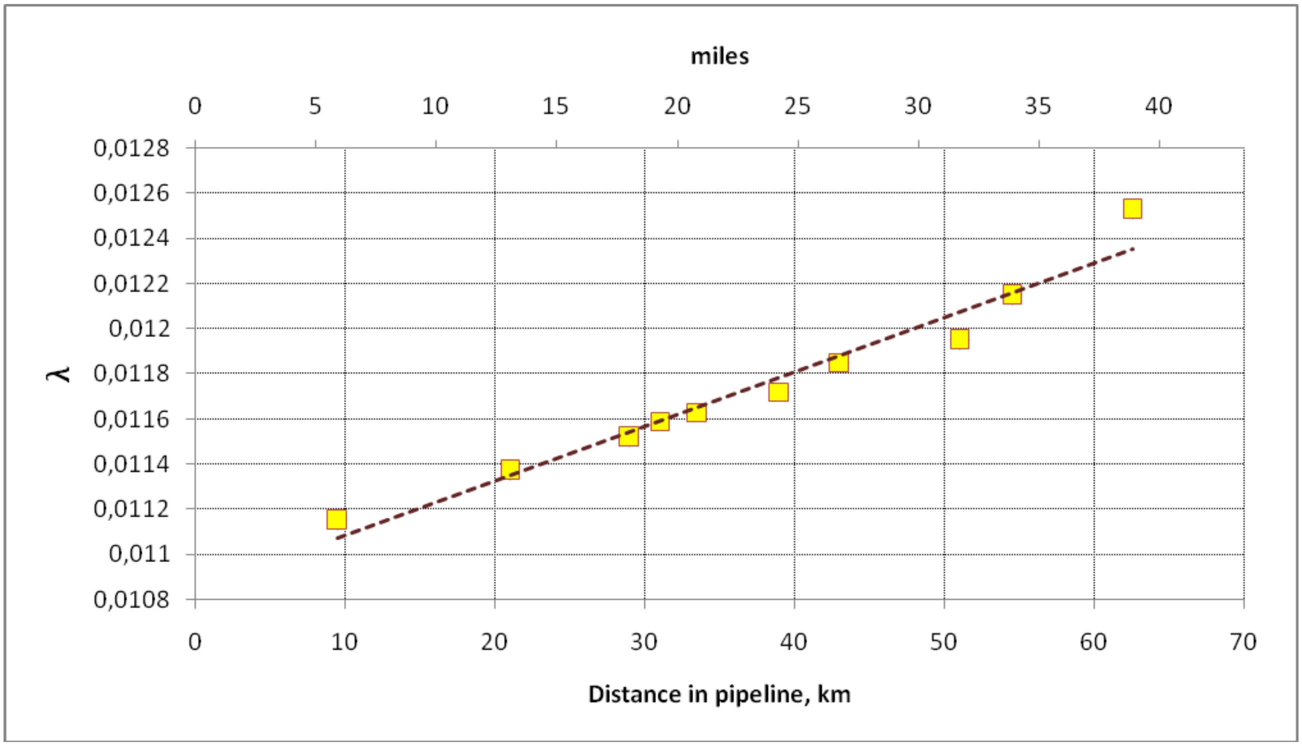

Figure 6 Dependence of hydraulic resistance on distance travelled by DRA in Pipeline#1 PS-2 – PS-3

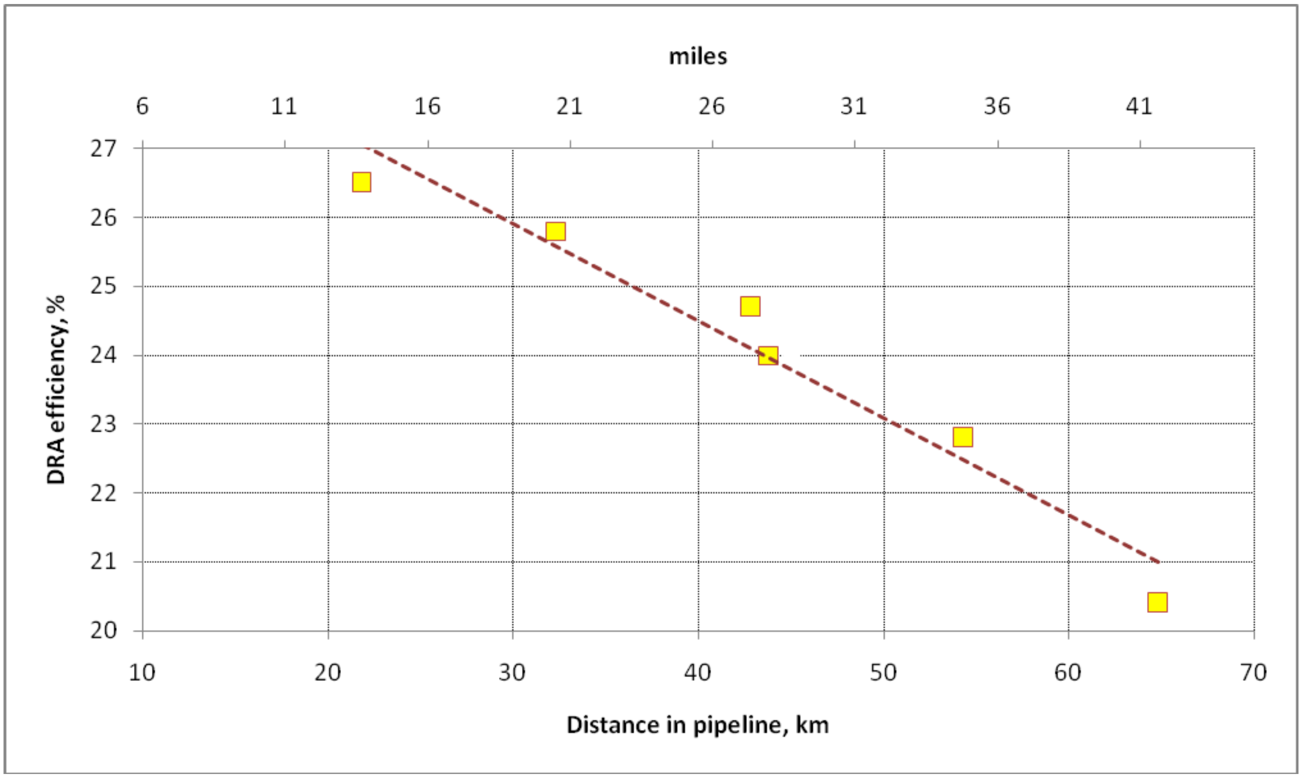

Figure 7 Dependence of efficiency on distance travelled by DRA in Pipeline#1 PS-1 –PS-2

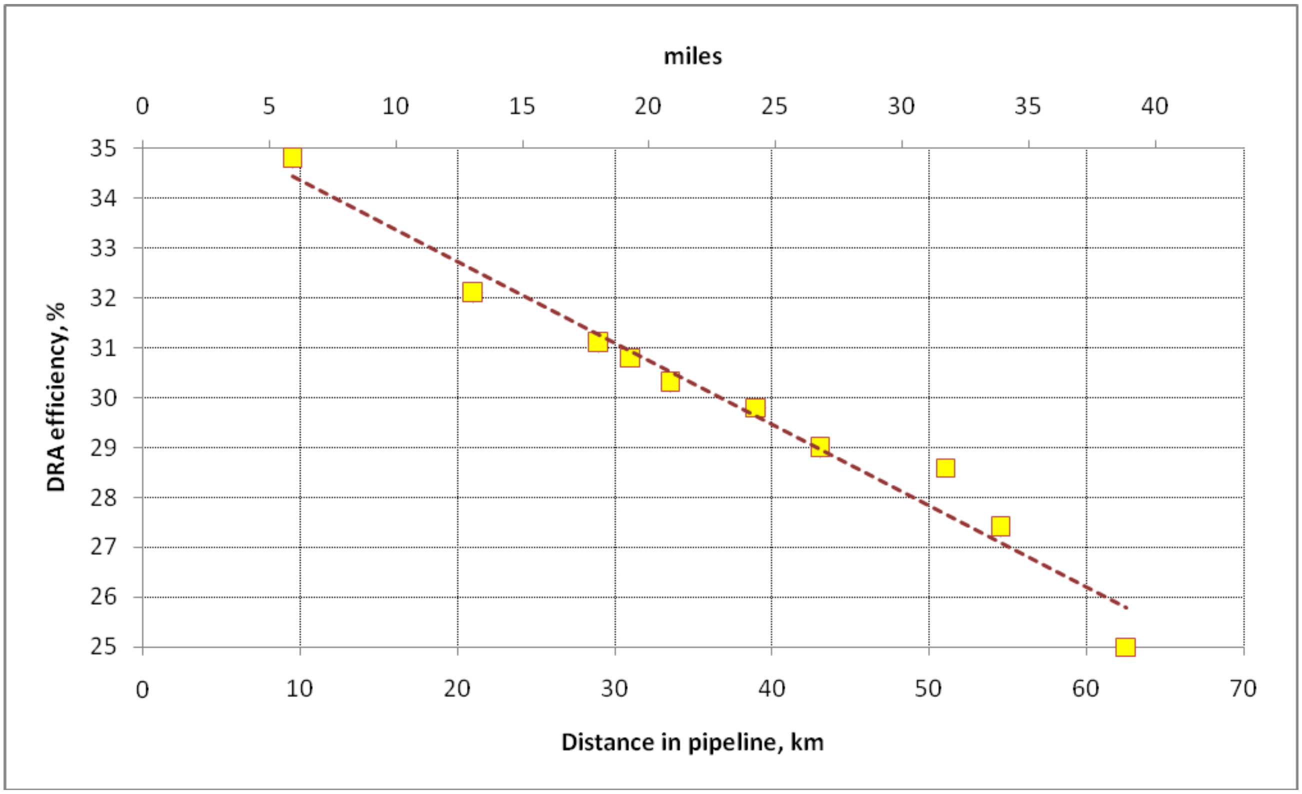

Figure 8 Dependence of efficiency on distance travelled by DRA in Pipeline#1 PS-2 – PS-3

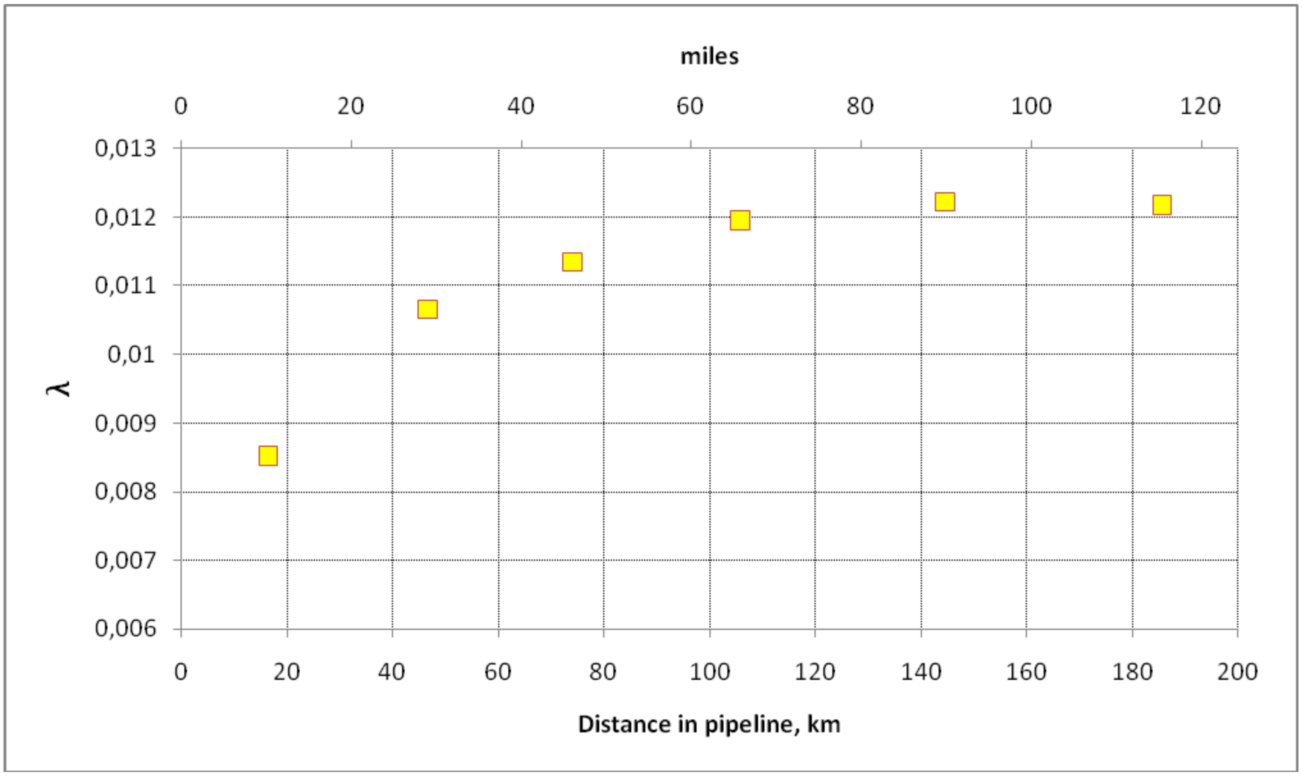

Figure 9 Dependence of hydraulic resistance on distance travelled by DRA in Pipeline#2

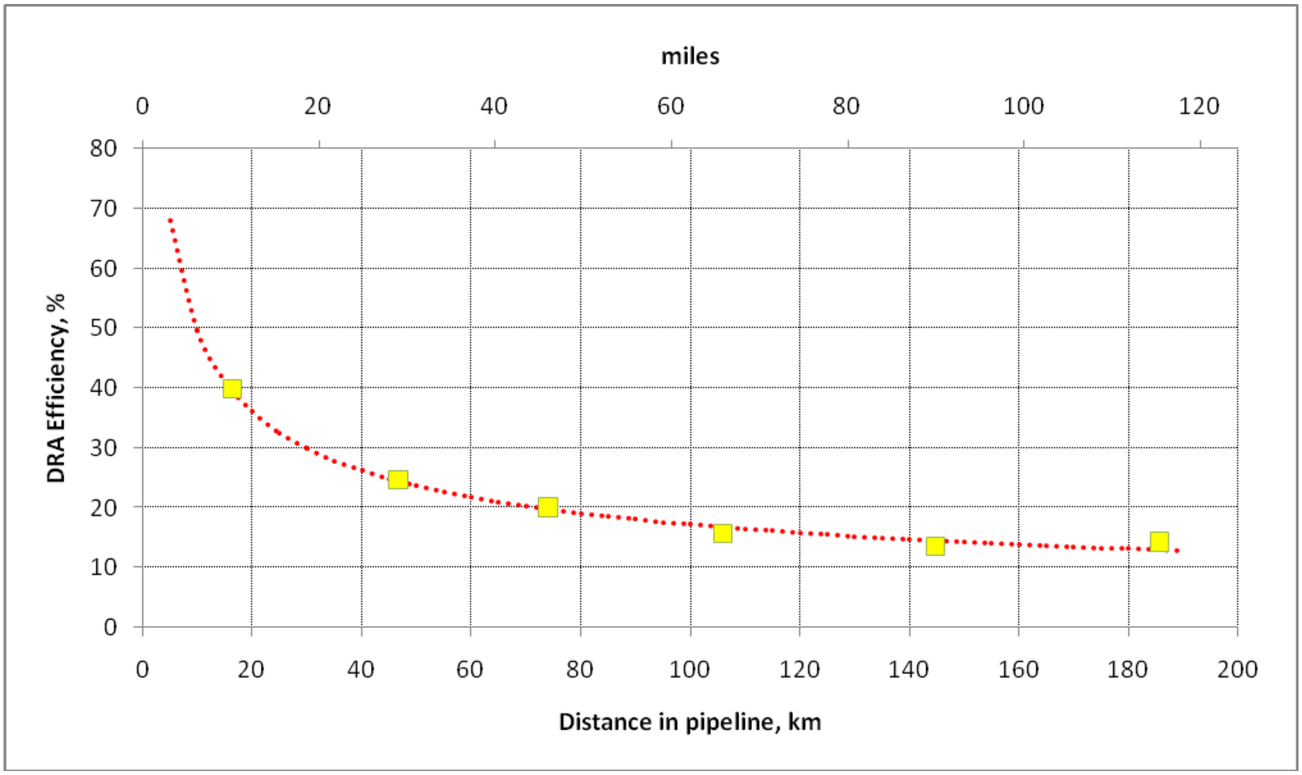

Figure 10 Dependence of efficiency on distance travelled by DRA in Pipeline#2

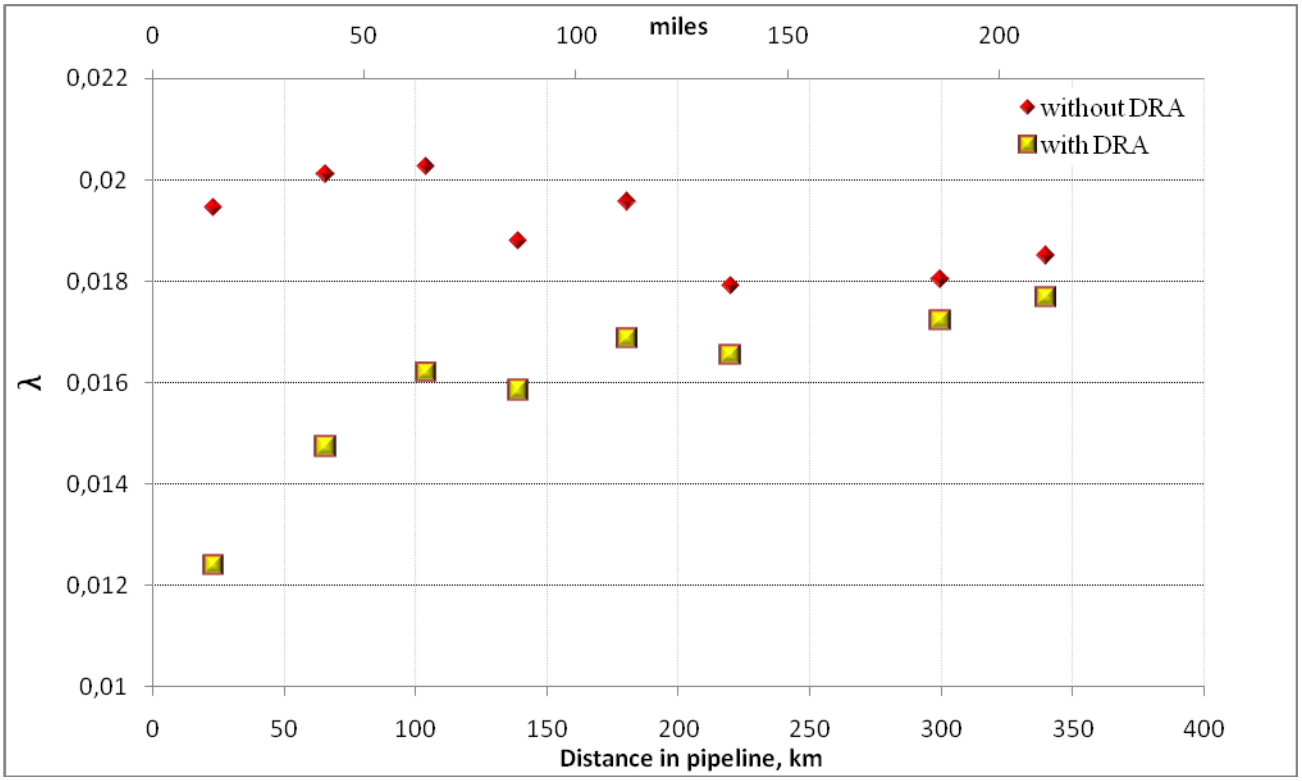

Figure 11 Dependence of hydraulic resistance ondistance travelled by DRA in Pipeline#3

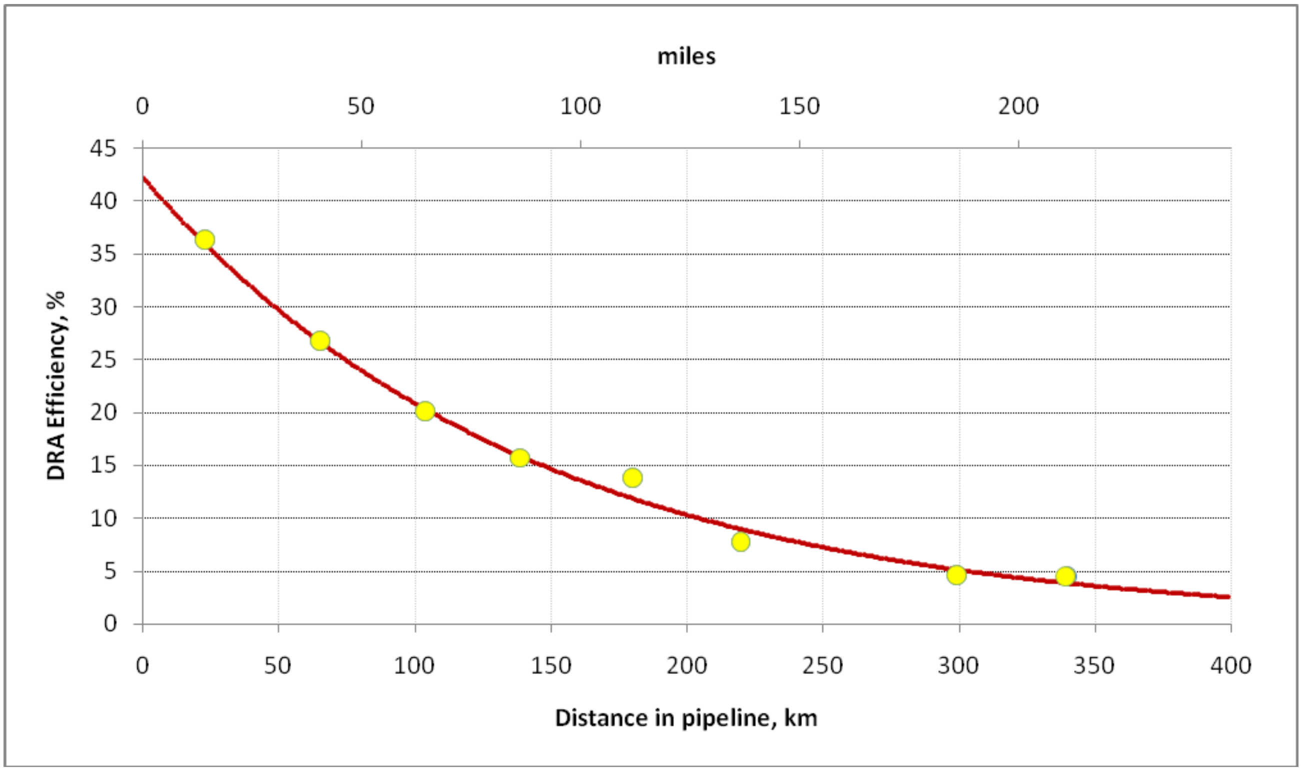

Figure 12 Dependence of efficiency on distance travelled by DRA in Pipeline#3