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Adaptation of fluid motion mathematical model in pipelines using drag reducing agents

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ABSTRACT

Presently one of the methods of increasing pipeline capacity is using the drag reducing agents (DRA). DRA are typically high molecular mass polymers that are added at very low concentrations to reduce the pressure drop necessary to generate a given flow rate in a turbulent flow. They can be used in case if building of extra loops or pumping stations is impossible or the need to increase pipeline capacity is seasonal. Scheduling pumping regimes and calculating the amount of drag reducing additive necessary to achieve the specified pumping parameters, requires a mathematical model. This paper propose a method that allows to integrate DRA into a mathematical model of viscous fluid motion in a pipeline. The model takes into account the degradation of DRA as the agents travel forward the pipeline.

This article focuses on the question of theoretical model adjustment to the characteristics of a certain pipeline. Using the nominal information about DRA (provided by manufacturers) generally leads to a strong error and some information needed for the modeling might not be provided at all.
Thus, the model needs to be tuned to the real DRA characteristics and the main source of data are real measurements of flow parameters (pressures, flow rates, etc.). Methods of using operational pipeline data for identifying DRA characteristics are considered. The issues of data collection and further data processing are discussed.
The results of comparing modeling computations with real data from operating pipelines are presented. The characteristics of these pipelines are very diverse: internal diameters vary from 0.4 m to 1 m, different DRAs are used, and different types of liquid (oils, oil products and gas-condensates) are pumped.

INTRODUCTION AND BACKGROUND

Adaptation or model tuning is highly important issue in mathematical modeling. The main goal of a model is to provide computations that are in good accordance with real measurements, so model should be adequately tuned. But there are always initially unknown or wrongly known physical parameters in any pipeline simulation. These will cause erroneous model results unless the model is calibrated to compensate for them. This is true for both predicitive models and real-time models.
Real-time models operate with active data. Generally, such models are used for detecting accidents, for example leaks, by comparing measured parameters and parameters calculated by model.
Predictive or simulation models don't have access to active data and are used for testing different scenarios, including those which may never have been attempted historically.
The process of model tuning becomes even more complicated in case of DRA usage.
Despite intensive research into the phenomenon of drag reduction with the help of chemical additives that have been going on more than for the past 70 years, there is still not a sufficiently complete theory of this phenomenon.
This is explained by the complexity of the problem, which lies at the junction of three sciences: physical chemistry of polymers, rheology and hydrodynamics.
Nevertheless, since the widespread use of DRA in pipelines, a technique is needed that allows to take DRA into account when modeling.
As can be seen in Figure 1, the characteristics of the additives provided by the manufacturers are quite general, so they should be verified using real measurements.

APPROACH

The first step of model tuning is to identify correct values of pressure sensors heights. This should be done once since it is highly unlikely for them to change. The procedure is the following: in static regime head values in a pipeline must be equal. The least squares method can be used to calculate the average head, then heights of sensors with large deviations of that average head can be corrected.

The accuracy of a mathematical model is estimated by comparing the computated flow rates and pressures with the real measurements. Most reasonable model parameters to tune are either the diameters or the hydraulic resistance, because there are physical processes that can change them. For example, diameters can decrease due to the waxing of a pipeline; they can change due to the corrosion or increase after scrapers pass. When DRA are not used, it is enough to adapt diameters of pipeline sections between pressure sensors to obtain reasonable model accuracy.

Adapted diameters are calculated from the Darcy–Weisbach equation using iterative Newton's method:

$$\Delta H = \lambda \frac{\rho u^2}{2D} L = \sum_i \lambda_i \frac{\rho_i u_i^2}{2 d_i} l_i$$

If we use Blasius formula for the hydraulic resistance coefficient λ, then diameter can be expressed explicitly from this equation. It should be noted that the same law for the hydraulic resistance coeffiecent should be used both in the adaptation process and in the following modeling.

Data stacks for adaptation must be gathered during steady state of pipeline flow. Naturally, in case of real-data models the sizes of time stacks for averaging the data should be chosen in such way that does not prevent accident detection, i.e. the time of data stack for adaptation should be significantly longer than the duration of the accident.

There is also a problem of choosing an appropriate law for hydraulic resistance calculation. However, since they are all empirical and no resistance equation is suitable for all pumping regimes, the law should be chosen based on convenience of computations as well. In addition, this is the reason to neglect pipeline roughness. There is no reliable method to adequately measure roughness on an operating pipeline. For the sake of model tuning accuracy, it is more convenient to use approximations for smooth pipelines, since otherwise we have to adjust not one, but two poorly measured parameters.

When DRA are used, there are two different approaches to identify DRA efficiency distribution over a pipeline.

For both of them first we need to identify how hydraulic resistance change over distance traveled by DRA in a pipeline. This is done similarly to the diameter adaptation in the absence of additives, we are solving Darcy–Weisbach equation for λ_i, assuming the diameters are known. In case of real-time model, this information is enough to provide required accuracy: with automatic hydraulic resistance tuning process real-time model will be accurate.

If there are measurements when pipeline was operating without DRA there is a technique to identify the dependence of the hydraulic resistance coefficient on distance traveled by DRA in pipeline.

If there are no such measurements, then it is possible to approximately estimate the hydraulic resistance without DRA using empirical formulas e.g. Blasius or Colebrook approximation, but this approach does not allow to take into account that hydraulic resistance usually is not completely uniform over the pipeline distance.

If the operating regime without DRA had a different flow rate from a regime with DRA, obtained hydraulic resistance coefficient should be normalized to the flow rate with DRA, because λ depends on flow rate and this misrepresent the efficiency trend:

$$\frac{\lambda_{Q0}}{\lambda_{Q\_DRA}} = \frac{\frac{0.3164}{\sqrt[4]{Re_0}}}{\frac{0.3164}{\sqrt[4]{Re_{DRA}}}} = \sqrt[4]{\frac{Re_{DRA}}{Re_0}} = \sqrt[4]{\frac{Q_{DRA}}{Q_0}}$$

$$\lambda_{0\_normalized} = \lambda_0 \sqrt[4]{\frac{Q_0}{Q_{DRA}}}$$

where $\lambda_{0\_normalized}$ is λ_0 without DRA normalized to flow rate with DRA.

It is certainly possible to continue adapting diameters while using DRA, but some issues may occur. Firstly, Newton's method, used in adaptation algorithm, is iterative, thus, it needs a good initial approximation. When a pipeline operates without DRA, nominal diameters are usually fit for this purpose. However, when DRA are used, adapted diameter can change significantly from nominal value to compensate for the drag reduction. Thus, Newton's method will not work correctly, the difference between the solution and the initial approximation is too large. Hydraulic resistance coefficient has a wider range of allowable changes. Secondly, adapting hydraulic resistance coefficients instead of diameters allows the simplest way to obtain valuable information about DRA behavior in a pipe, which can be used in predictive models.

Integrating DRA into predictive model equations is a sequential process of identifying the following relations: $\lambda(x) \rightarrow \varphi(x) + \varphi(C) \rightarrow C(x)$

We need to convert the initial relation $\lambda(x)$ into $C(x)$, so we can model processes when DRA concentration is changing.

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

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

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.

As we will see below, it is highly desirable to get the λ(x) dependency, since empirical approximations do not give all the information about the local features of a pipeline, which can significantly affect the value of hydraulic resistance
The relation between the DRA efficiency and concentration is usually described as following [2]:

$$\varphi(\mathrm{C}) = \varphi_{max}\frac{\alpha C}{1+\alpha C},$$

where φ_{max} is the maximum efficiency that could be obtained using given DRA, C – DRA concentration and α – constant specific for the given DRA. It should be noted here that there is a peak DRA concentration at which maximum efficiency is reached and further increasing of DRA concentration does not increase its efficiency. If there are experimental data with different DRA concentrations, it is possible to specify $\varphi(\mathrm{C})$ for a given pipeline. Assuming that maximum efficiency is achieved at maximum (starting) concentration, we take the maximum efficiency from the distribution φ(x) and set in accordance with the starting concentration.
Knowing φ(x) and $\varphi(\mathrm{C})$ we can obtain C(x) that can be used in the predictive mathematical model and allows to model regimes with changing concentration.

ANALYSIS

The experimental results were gathered from the operating pipelines with the characteristics given in the section. Schemes of studied pipelines are presented in Figure 2. The figures show the relative coordinates of the pipeline objects from the beginning of the considered section.

Pipeline I

Gas-condensate pipeline, inner diameter 0.4 m (15.75 inches), density varies from 680 kg/m^3 (5.67 Ib/gal) to 725 kg/m^3(6.05 Ib/gal), viscosity varies from 0.7 cSt to 2 cSt, oil flow from 248 m^3/h (1092 gal/min) in the beginning of the pipeline to 700 m^3/h (3082 gal/min) at the end of the considered section, flow velocity from 0.55 m/s (1.23 miles/hour) to 1.54 m/s (3.44 miles/hour), Reynolds number approximately 310 000.
There are midline product injections at 16.5 km, 142.2 km, 150.4 km, 176.3 km and 308 km. In addition, there is a loop which begins at 176.3 km and ends at the outlet of the pipeline at 327.8 km. DRA are injected at the beginning of the pipeline (0 km) and with the midline injection at 308 km. DRA were injected in concentrations 30, 35, 50 and 65 ppm.

Figures 3-5 present distribution of hydraulic resistance coefficients over distance in the pipeline λ(x), distribution of DRA efficiency over distance φ(x), and fact and calculated head, respectively.

Pipeline II

Diesel pipeline, inner diameter 0.5 m (19.69 inches), density 830 kg/m^3 (6.93 Ib/gal), viscosity 3-4 cSt, flow 920 m^3/h (4050 gal/min), flow velocity 1.3 m/s (2.9 miles/hour), Reynolds number 217000. In the first pipeline section there is a loop, which is operating simultaneously with DRA usage.
The length of the studied area in the pipeline is 227 km, this area is located between two pumping stations, DRA are injected at the beginning of the area.
Figures 6-8 present distribution of hydraulic resistance coefficients over distance in the pipeline λ(x), distribution of DRA efficiency over distance φ(x), and distribution of DRA efficiency over distance C(x), respectively.

Pipeline III

Oil pipeline, inner diameter 0.8 m (31.5 inches), density 860 kg/m^3 (7.18 Ib/gal), viscosity 12 cSt, oil flow 2900 m^3/h (12800 gal/min), flow velocity 1.63 m/s (3.64 miles/hour), Reynolds number 107000. DRA injected at the beginning of the pipeline (0 km) after the first pumping station.
The same flow rate is obtained in one case due to the DRA, in the other due to the operating of the second pumping station.
Figure 18 shows the dependence of the concentration on DRA efficiency in the Pipeline III.
This dependence was plotted using the data from the DRA passport, because this pipeline operates with only one DRA concentration, so it impossible to verify it using real data.
Figures 9-11 present distribution of hydraulic resistance coefficients over distance in the pipeline λ(x), distribution of DRA efficiency over distance φ(x), and distribution of DRA efficiency over distance C(x), respectively.

Pipeline IV

Oil pipeline, inner diameter 1 m (39.37 inches), density 844 - 855 kg/m^3 (7.04 – 7.14 Ib/gal), viscosity 7 - 12 cSt, oil flow 2700 m^3/h (11890 gal/min), flow velocity 0.91 m/s (2.04 miles/hour), Reynolds number 95000.
Graph in Figure 18 shows the dependence of the concentration on DRA efficiency in the Pipeline IV. Both dependencies are for the same type of DRA, but the graph plotted by red circles presents data from autumn pumping (the highest oil temperature of the year) and the the graph plotted by green circles presents data from spring pumping (the lowest oil temperature of the year). DRA were injected in concentrations 5, 8 and 12 ppm at autumn trials and 5, 8, 12, 18, 25 ppm at spring trials.

This dependence of efficiency on concentration was identified using real measurements. The same DRA brand as in Pipeline III was used, so it is possible to see how this dependence fits DRA passport characteristics.
Figures 12-14 present autumn distribution of hydraulic resistance coefficients over distance in the pipeline λ(x), distribution of DRA efficiency over distance φ(x), and distribution of DRA efficiency over distance C(x), respectively. Figures 15-17 present the same information for the spring DRA trials.

RESULTS

Figure 3 presents adapted hydraulic resistance coefficients in Pipeline I. There are few possible explanations: gas caverns can exist in the pipe; different condensates are mixing; there are many zones with different flow rates and consequently different flow regimes in this pipeline; there is also a loop.
Still we can make some general observations. Figure 4 shows efficiency distribution over distance for different DRA concentrations. Although some efficiency values are definitely non-physical (below zero efficiency), we can note that generally efficiency increases with concentration and the difference between high and low concentrations becomes more distinguished with the increase of flow rate. As it can be seen in Figure 5, it is possible to adapt hydraulic resistance coefficients for the real-time model.
Figure 18 presents φ(C) distributions (efficiency over concentration) for the studied pipelines. These are passport ones for Pipeline II and Pipeline III and identified ones for Pipeline I and Pipeline IV. Results for Pipeline I may be controversial due to the atypical DRA behavior in this pipeline; maximum DRA efficiency is reached not near the point of DRA injection, but after significant flow rate increase due to the midline condensate injection. Albeit φ(C) in Pipeline I looks similar to φ(C) in other pipelines.
φ(C) distribution for Pipeline IV (autumn) is in good accordance with passport characteristics of this DRA brand. Wherein these distributions differ for spring and autumn trials in Pipeline IV, but it is complicated to find the exact reason for this, because oil density/viscosity/temperature change simultaneously, so it is therefore unclear which parameter exactly makes a greater contribution to the effect.
In most of considered pipelines DRA concentration reduces as DRA move down a pipeline. The most common explanation is that this process is caused by mechanical degradation of the DRA polymer chains. Regardless of the mechanism of this process, the concentration and the efficiency of DRA decreases as DRA move down a pipeline, respectively increases the coefficient of hydraulic resistance.
Blasius and Colebrook (Swamee-Jain approximation for smooth pipelines) in most cases show relatively good convergence with real data.
In most experiments, DRA activation zone is observed. Except Pipeline I, another case where activation zone is not seen is autumn trials in Pipeline IV. Possibly, it can be explained that DRA activation accelerates in oil with higher temperature and lower viscosity.

As we can see from Figures 8, 11, 14 and 17, exponential approximation $C(x) = (\mathrm{C}_0 - \gamma e^{\delta x})$ over the entire length of the plot is worse than a power law $C(x) = \alpha x^{\beta}$. Still many works like [3] propose to use exponential function to describe the process of DRA degradation. The exponential approximation looks more physical since, unlike the power function, with zero distance traveled, it gives an initial concentration. From the point of view of the physical meaning, it is better to break up the process of DRA degradation into zones, in each of which the degradation of additives is described by a selected law (exponential approximation fits better at the first half of the distance).
For the sake of computation convenience, it is better to choose one function optimal over the entire length of a pipe. However, activation zone should be taken into account in both cases.

CONCLUSIONS

There is the problem of choosing a suitable function to approximate the process of DRA degradation. Although some general patterns can be noted, the behavior of DRA under different conditions is so diverse that it is still difficult to design a single model describing their behavior in all cases.

In general, for the sake of modeling accuracy, the best option is the identification of the empirical dependence of the concentration 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 in the same pipeline.

Although a strict theory of DRA phenomenon does not yet exist, it is possible to design an empirical algorithm that allows to customize both online and offline models. In case of online model this algorithm needs to be automatic to continuiosly ensure good accuracy of computations.

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AUTHORS BIOGRAPHY

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FIGURES

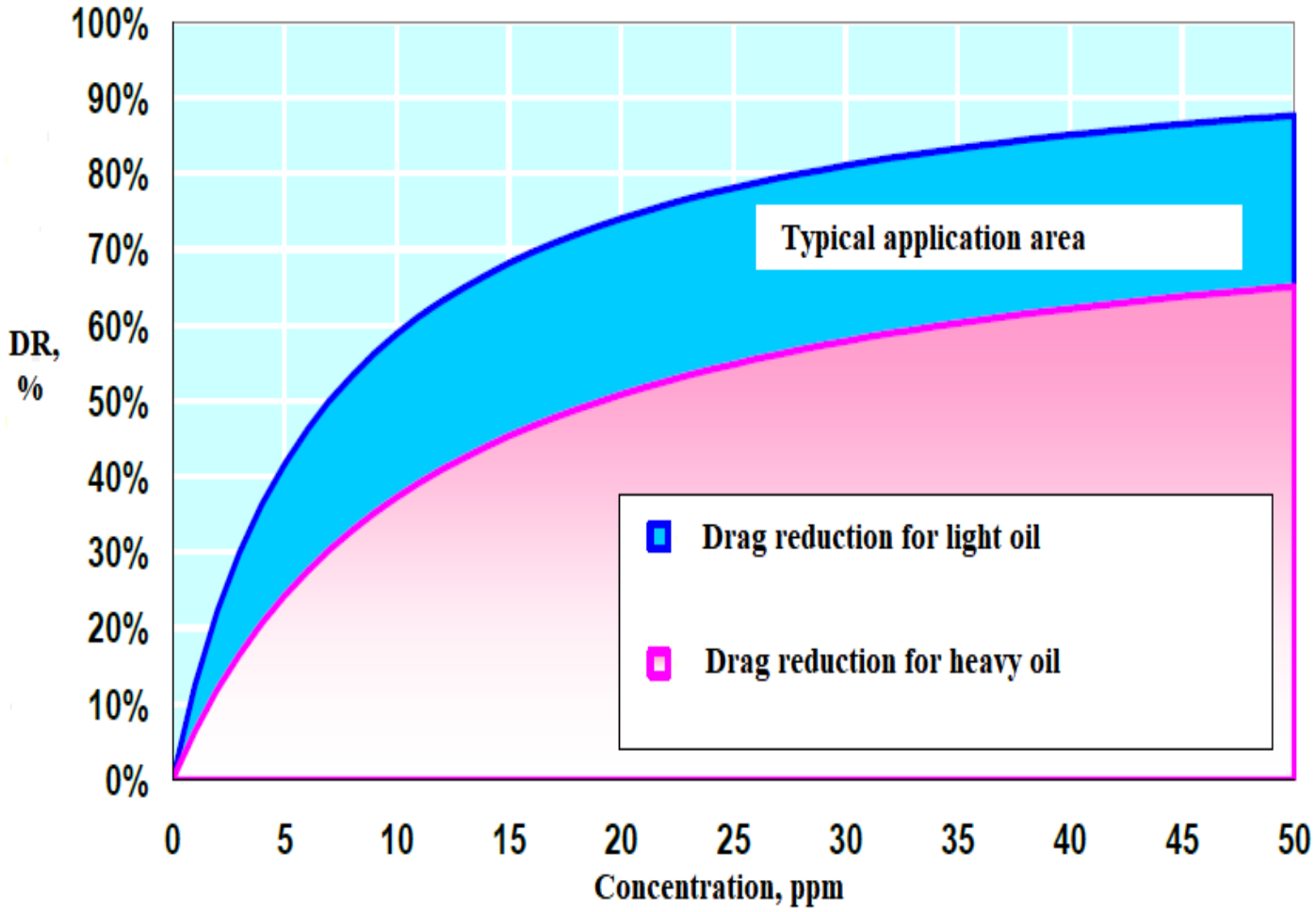


Figure 1 Typical relation of DRA efficiency on concentration

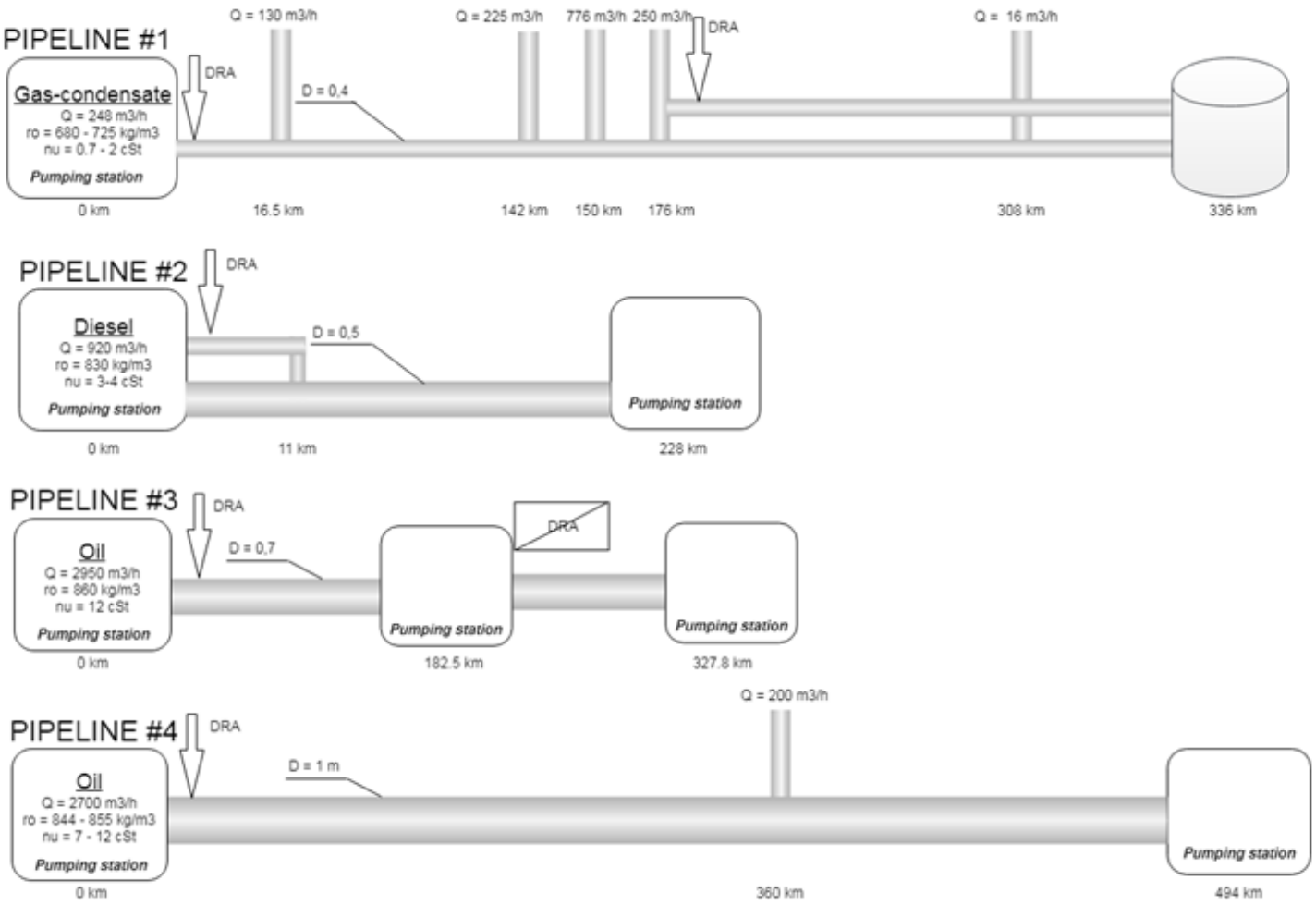


Figure 2 Schemes of studied pipelines

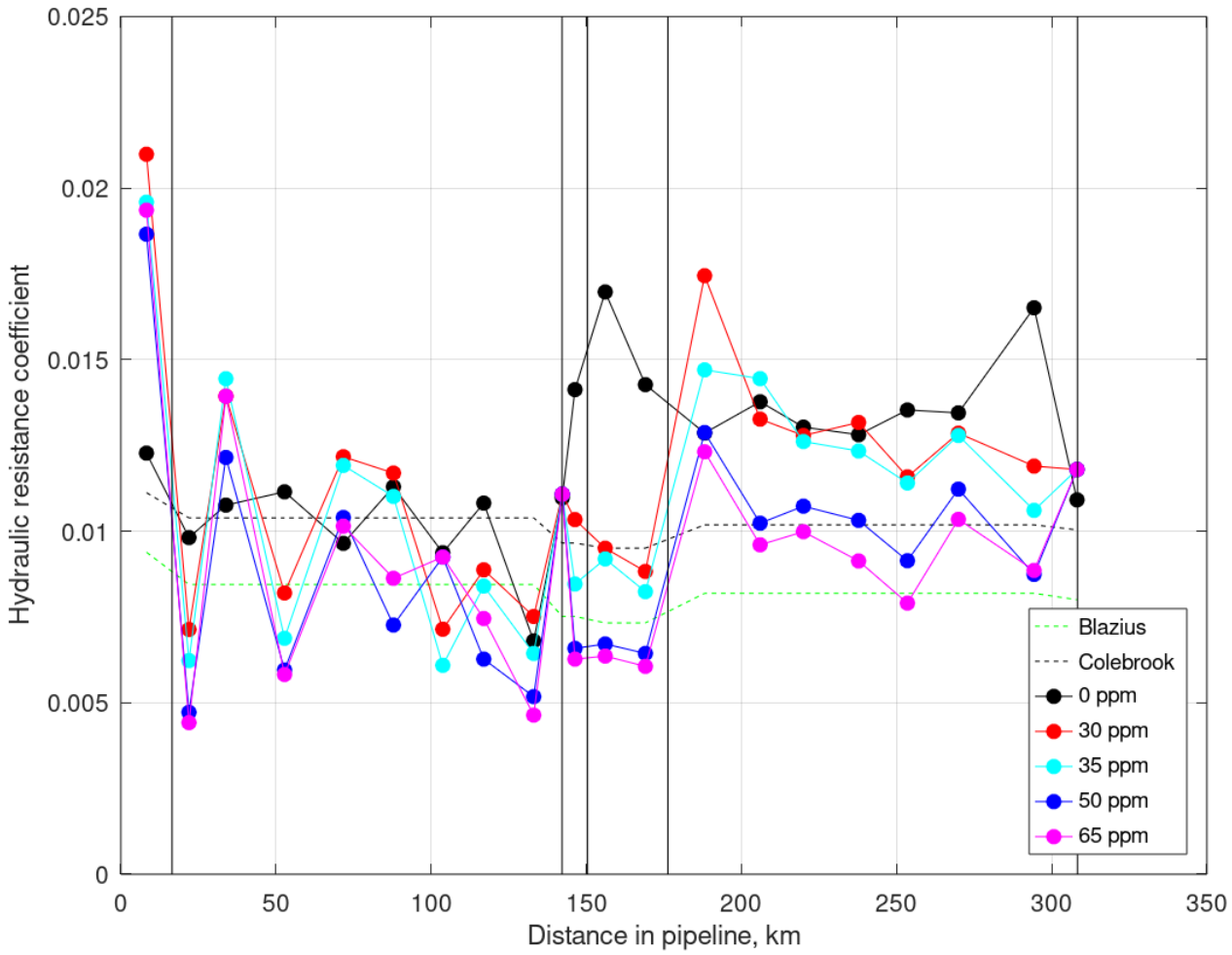


Figure 3 Hydraulic resistance coefficient distribution over travelled distance, Pipeline I. Vertical black lines mark locations of midline injections.

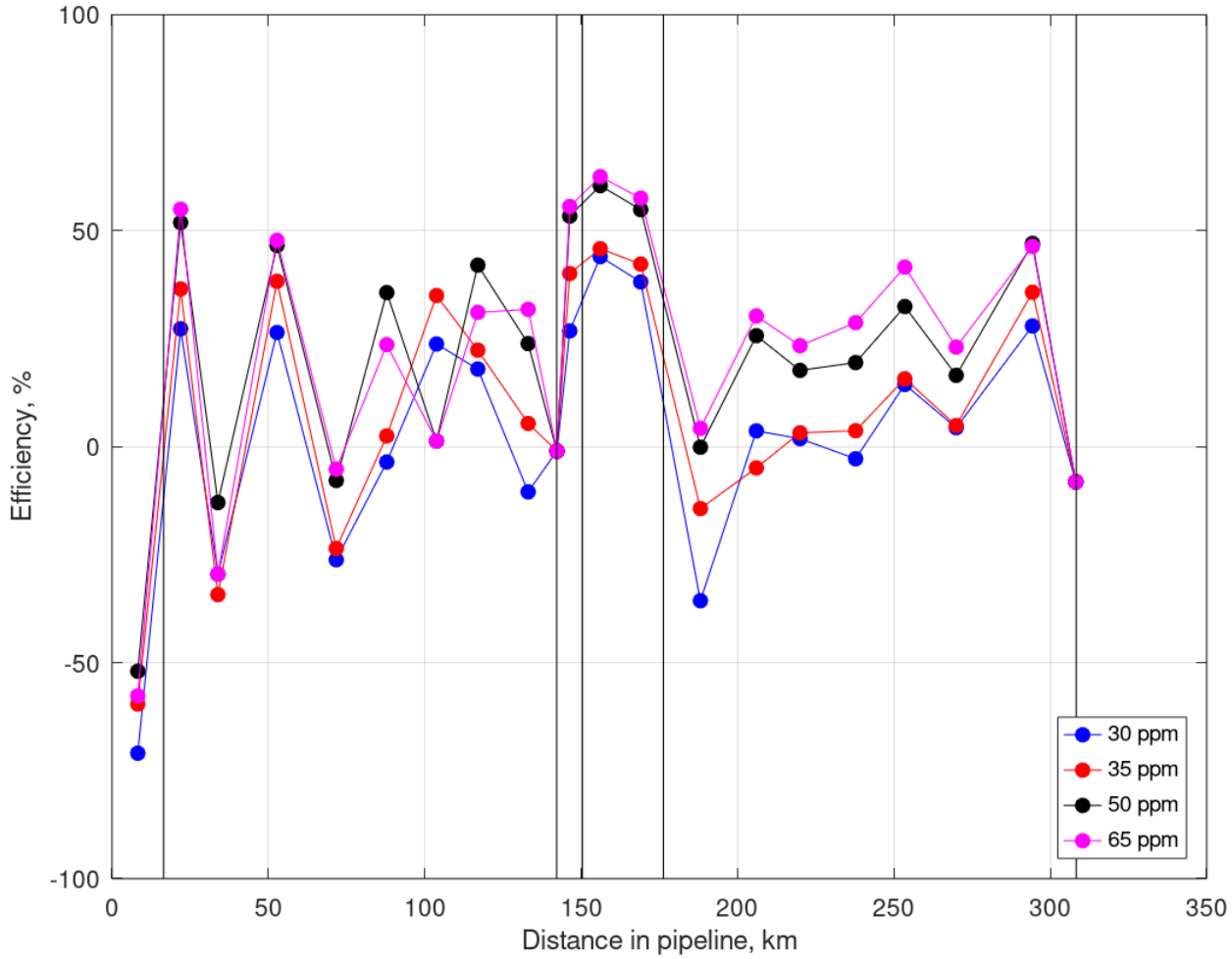


Figure 4 DRA efficiency distribution over travelled distance, Pipeline I. Vertical black lines mark locations of midline injections.

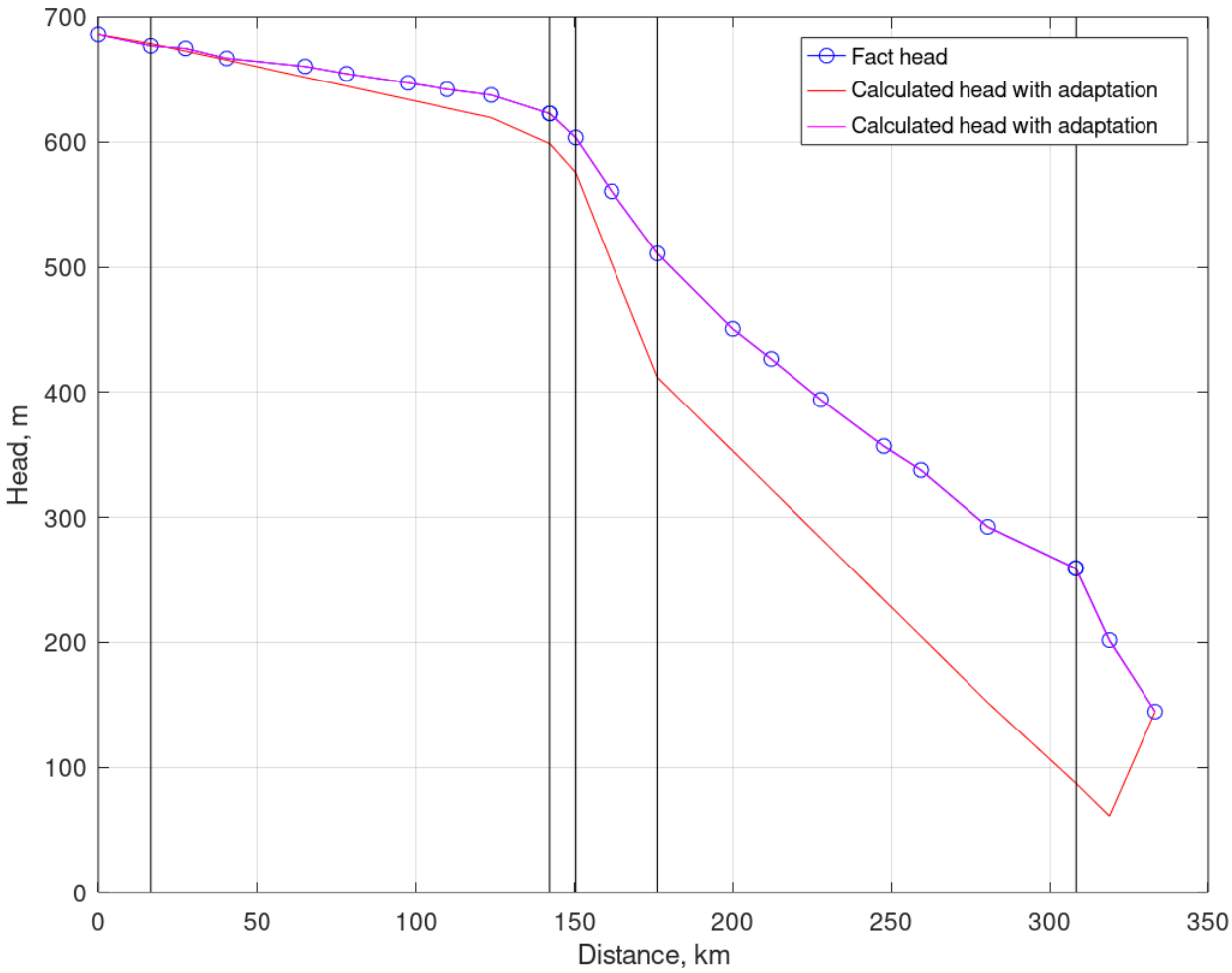


Figure 5 Fact and calculated heads, Pipeline I. Vertical black lines mark locations of midline injections.

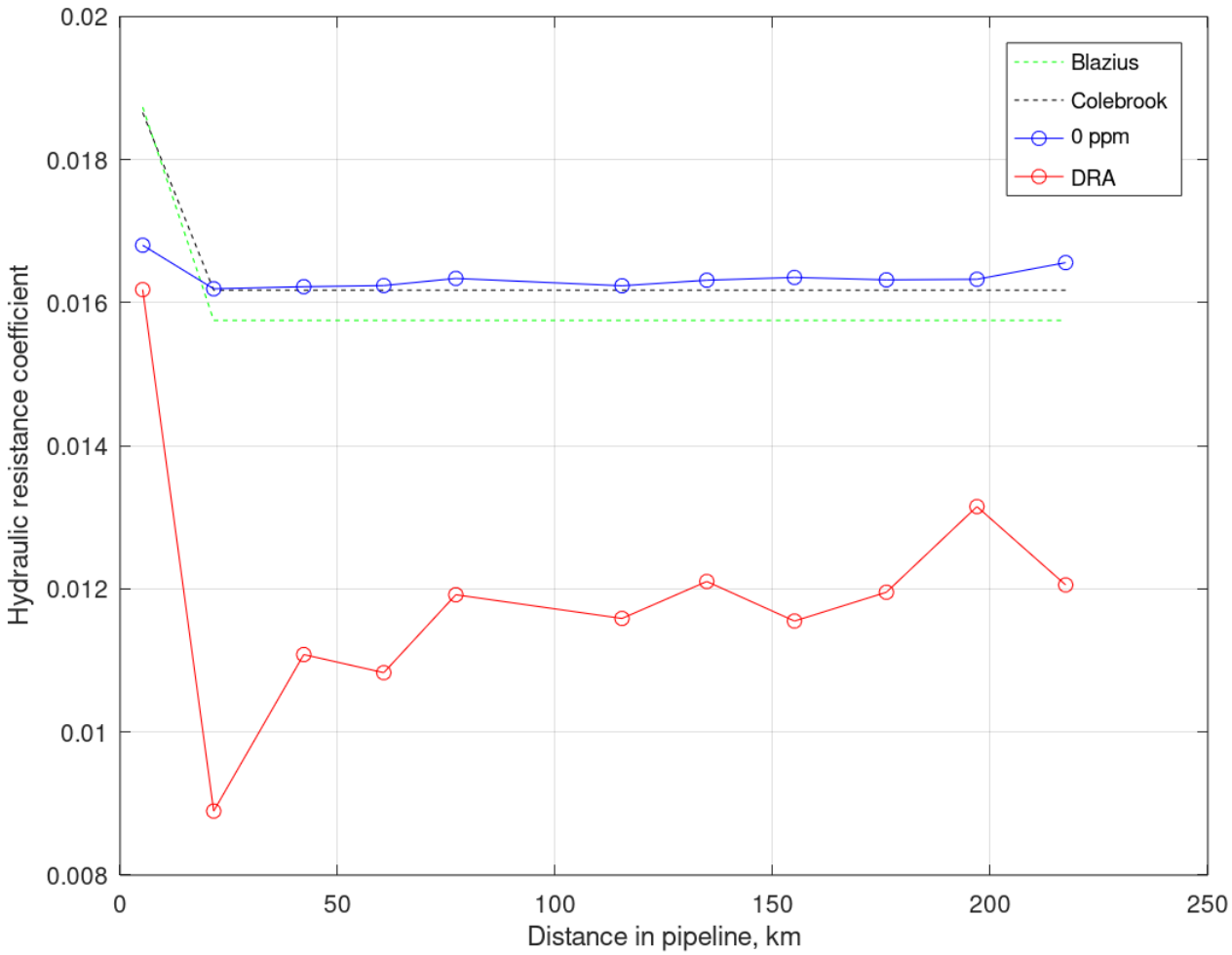


Figure 6 Hydraulic resistance coefficient distribution over travelled distance, Pipeline II.

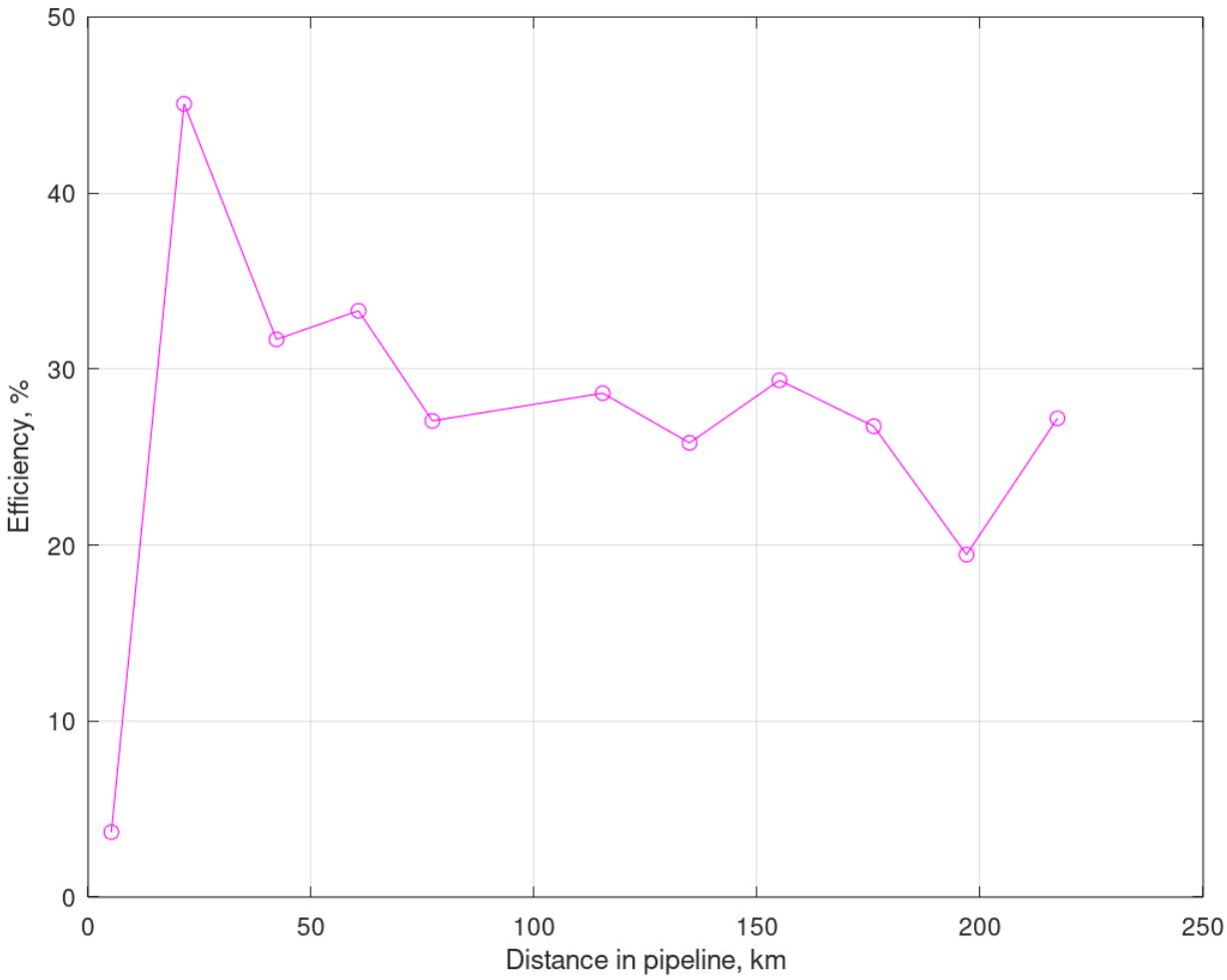


Figure 7 Efficiency distribution over travelled distance, Pipeline II

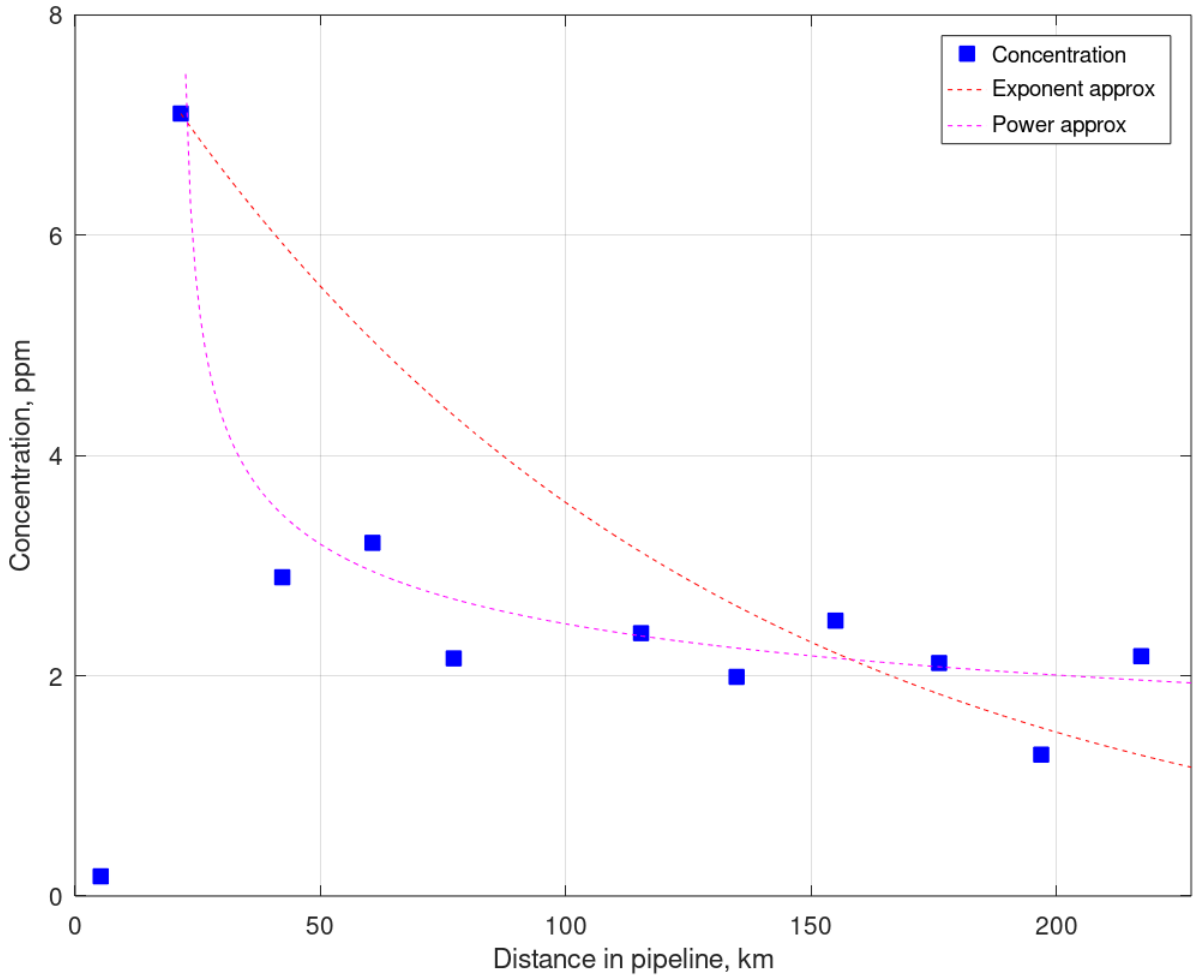


Figure 8 Concentration distribution over travelled distance, Pipeline II

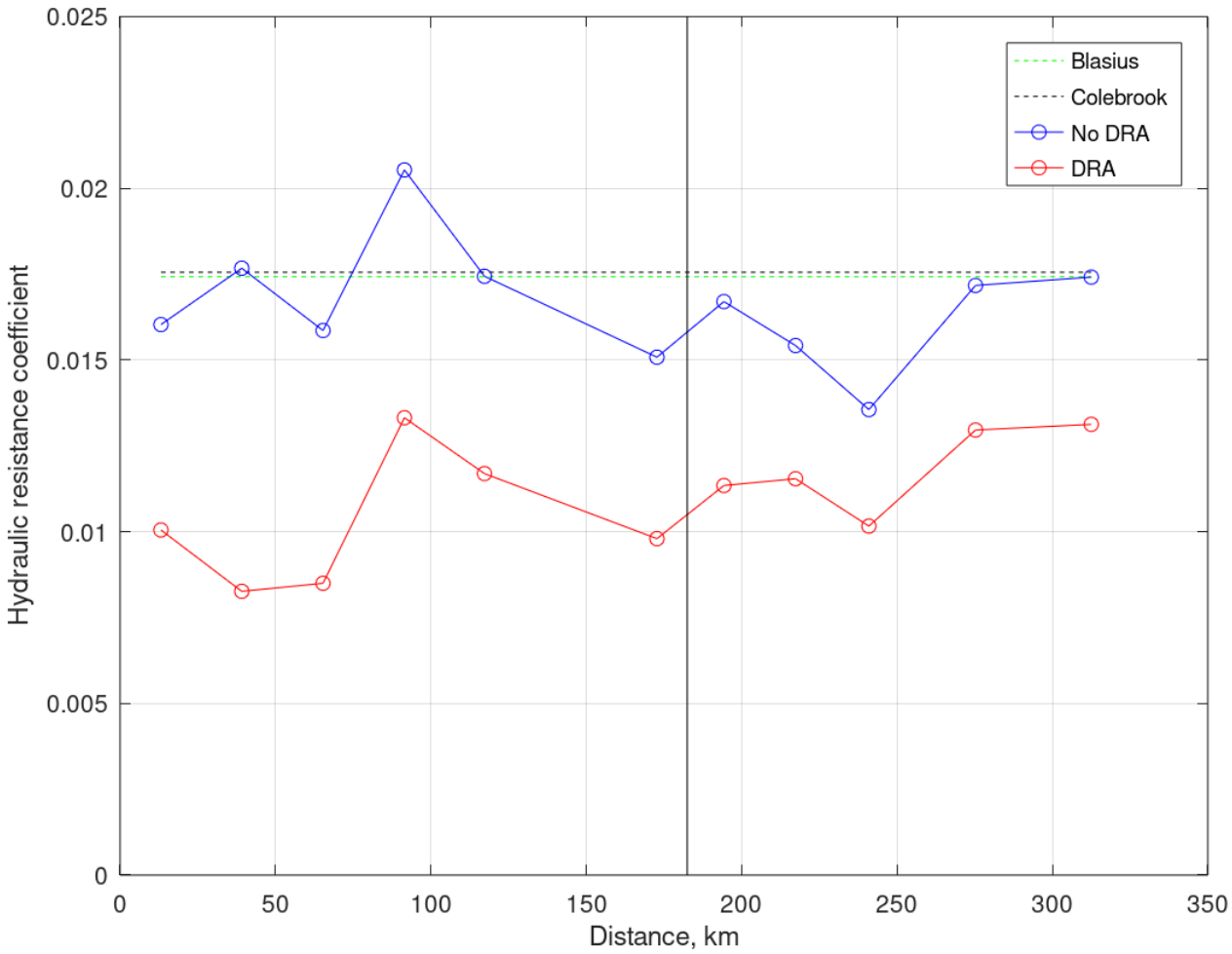


Figure 9 Hydraulic resistance coefficient distribution over travelled distance, Pipeline III

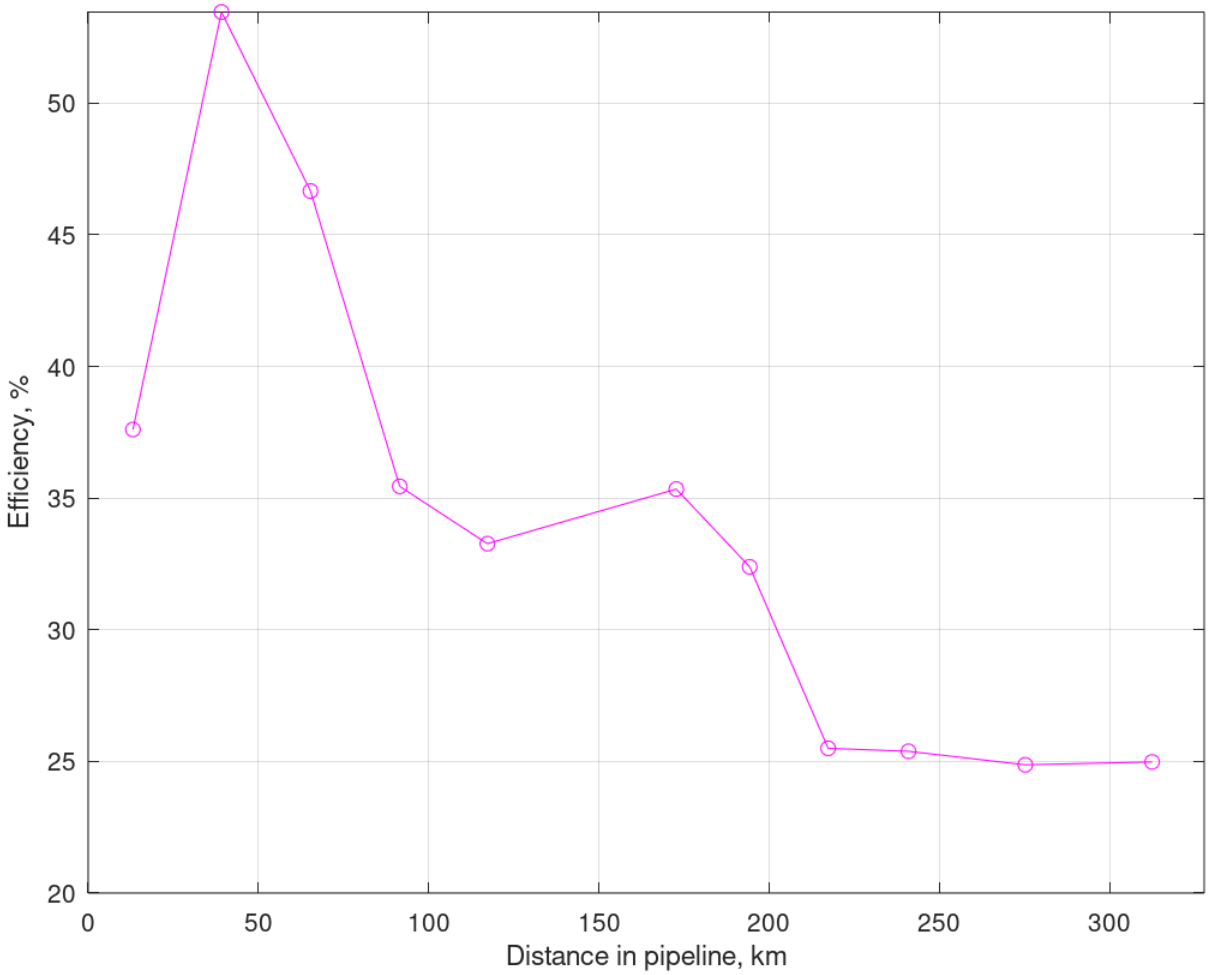


Figure 10 Efficiency distribution over travelled distance, Pipeline III

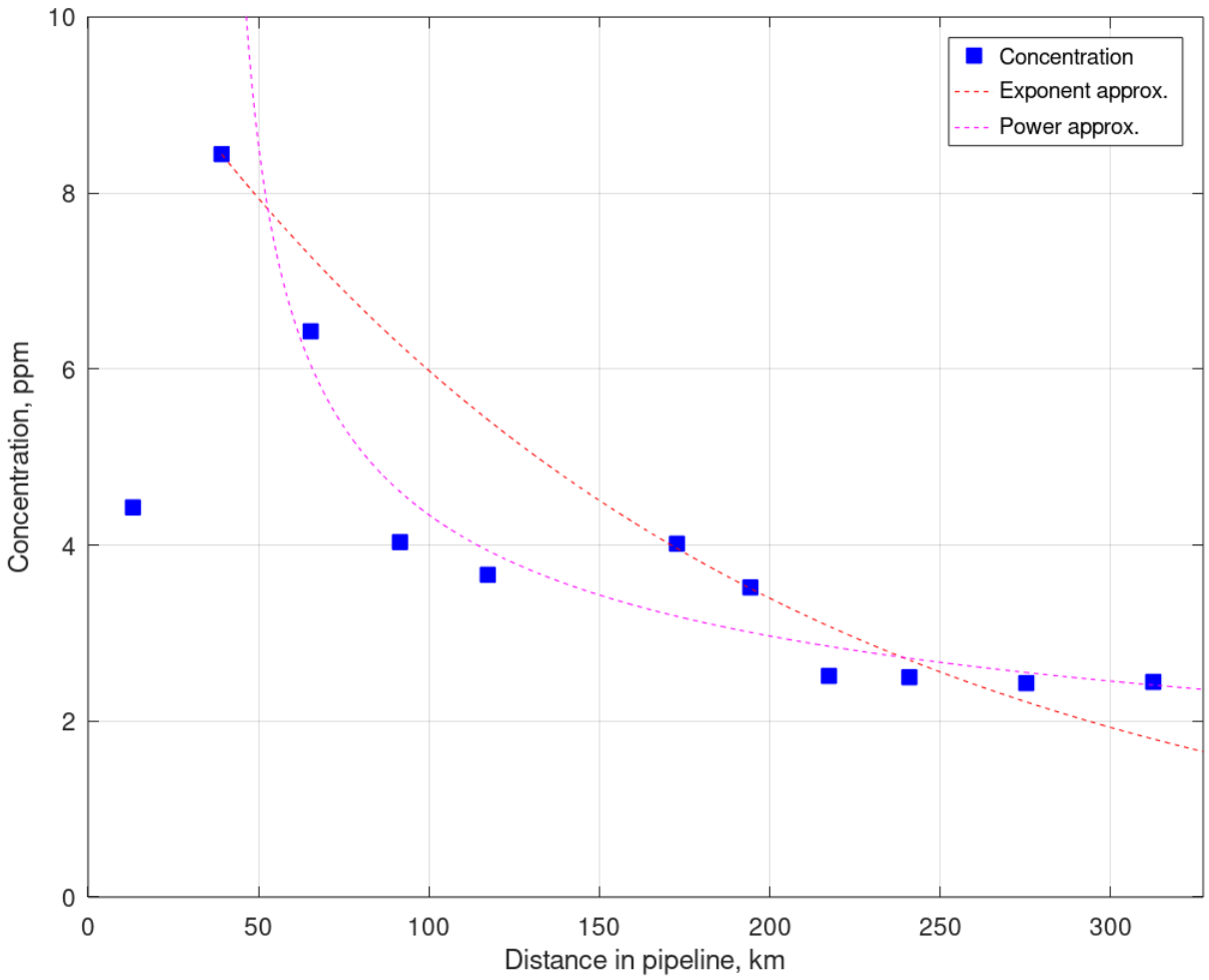


Figure 11 Concentration distribution over travelled distance, Pipeline III

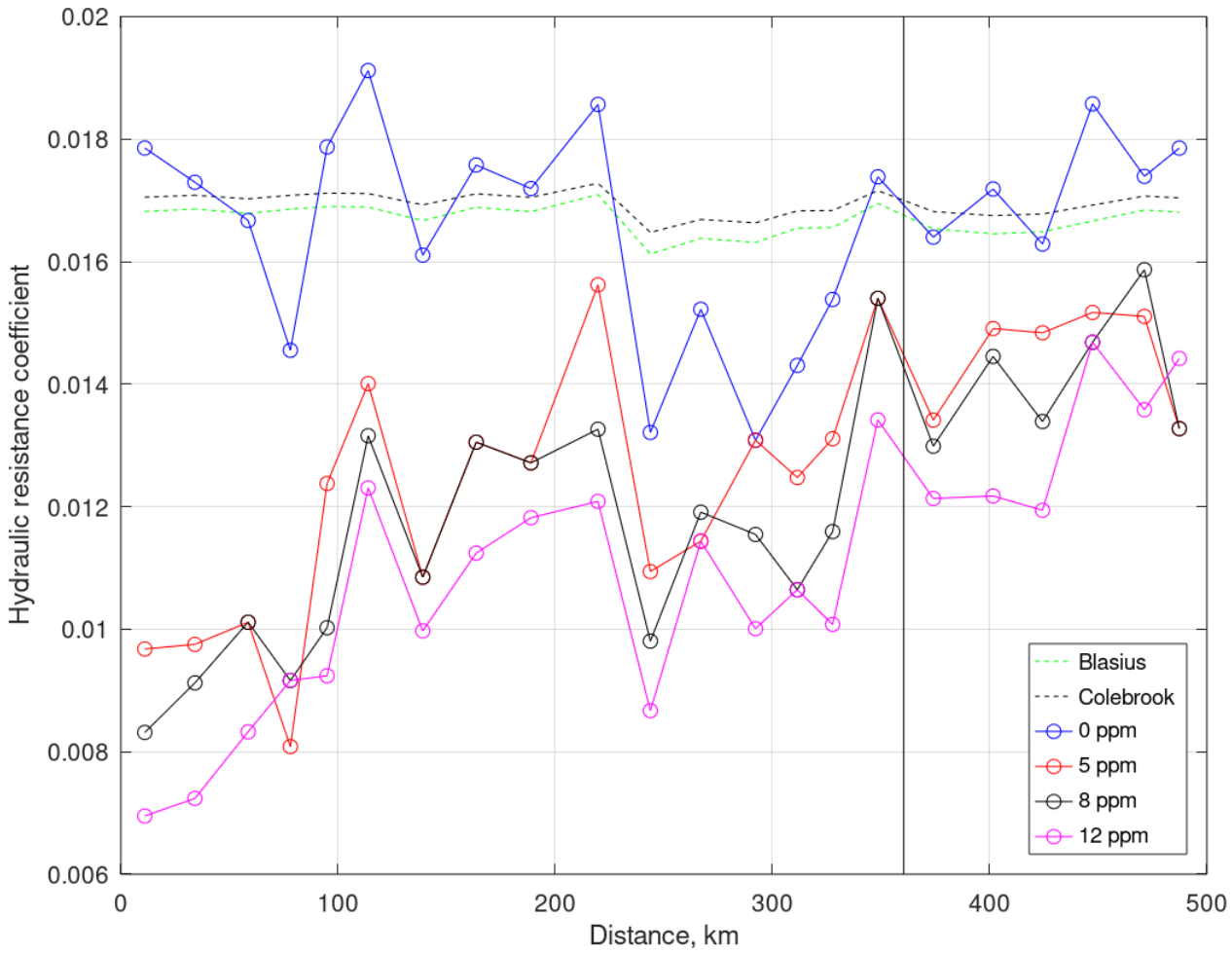


Figure 12 Hydraulic resistance coefficient distribution over travelled distance, Pipeline IV autumn

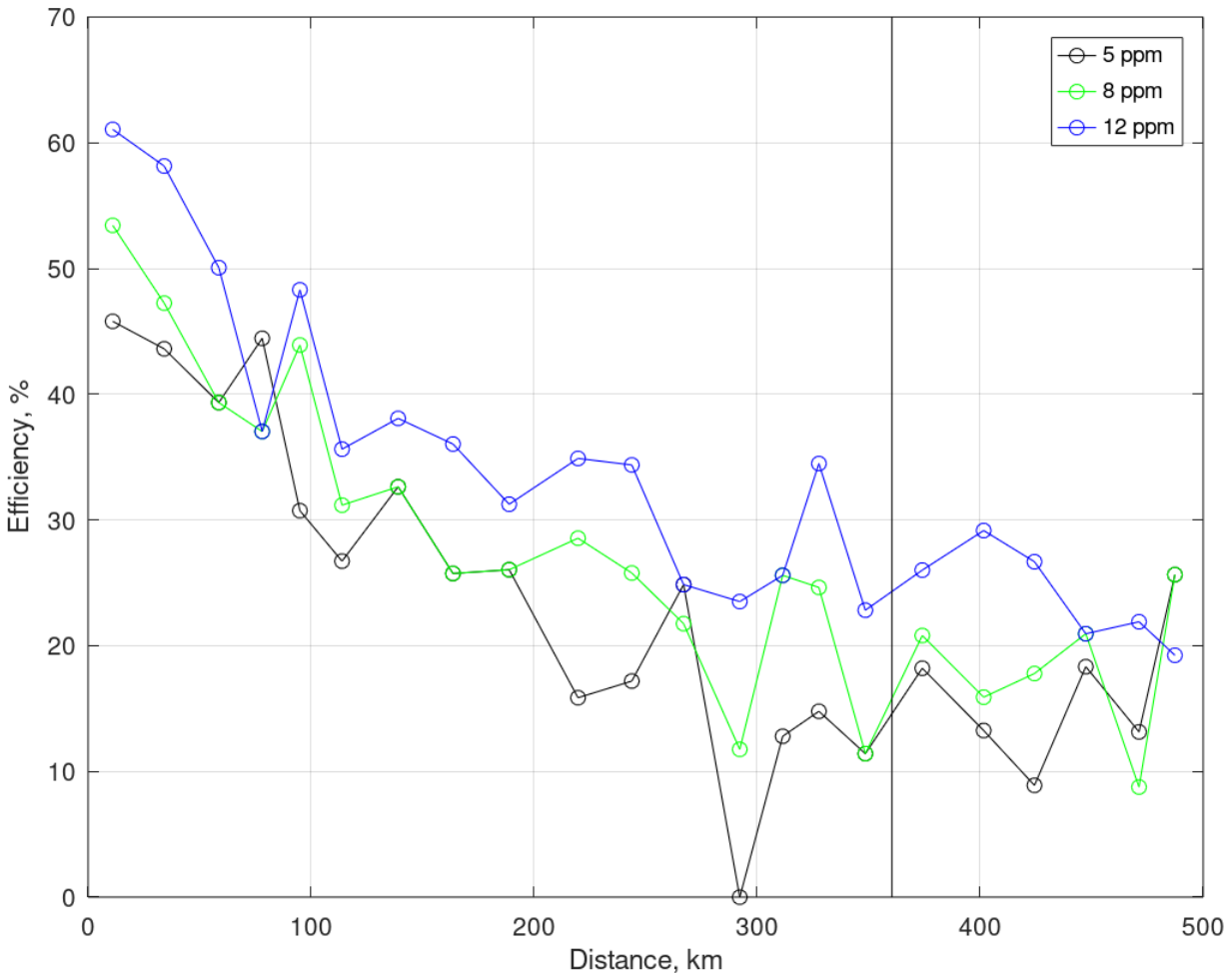


Figure 13 Efficiency distribution over travelled distance, Pipeline IV autumn

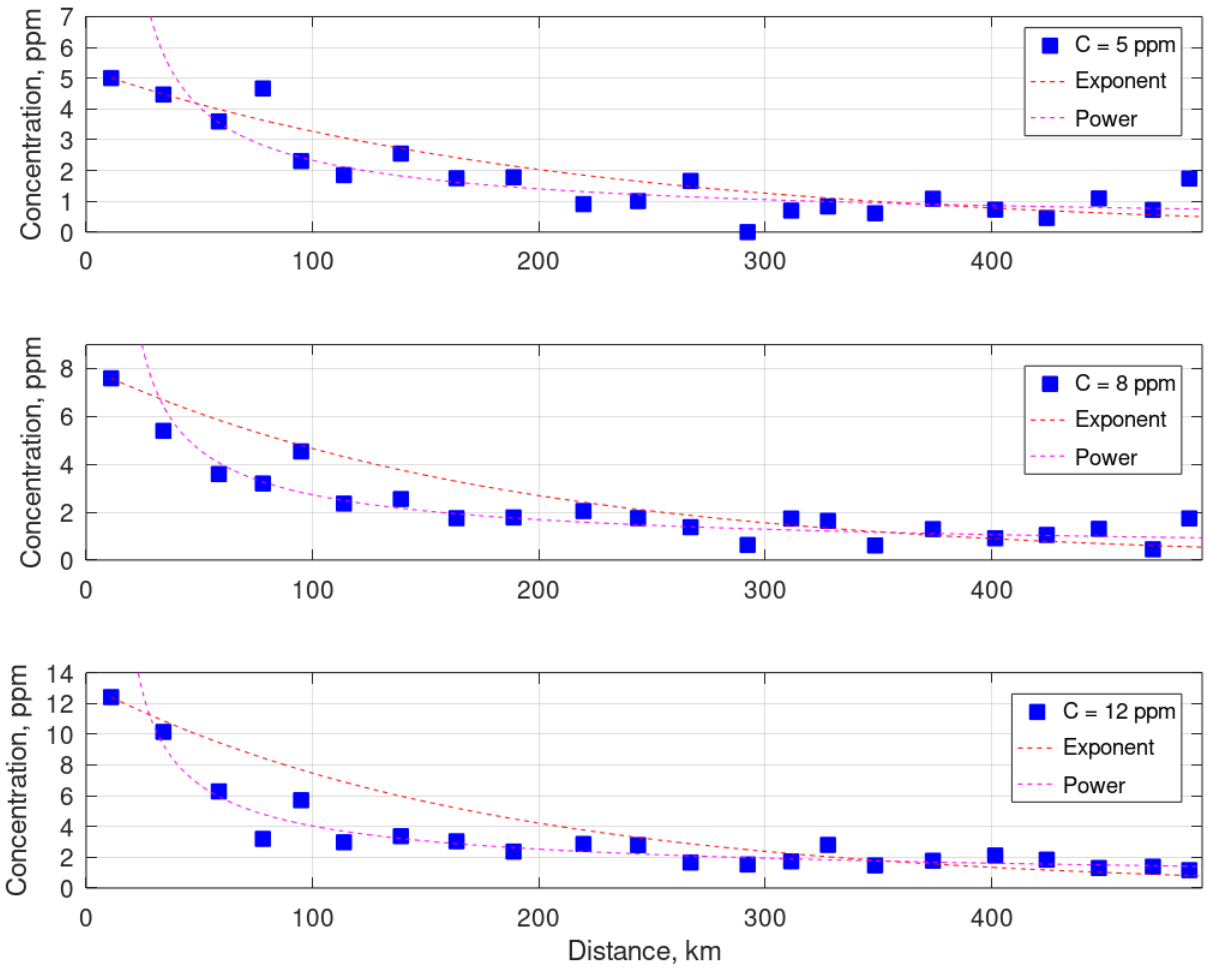


Figure 14 Concentration distribution over travelled distance, Pipeline IV autumn

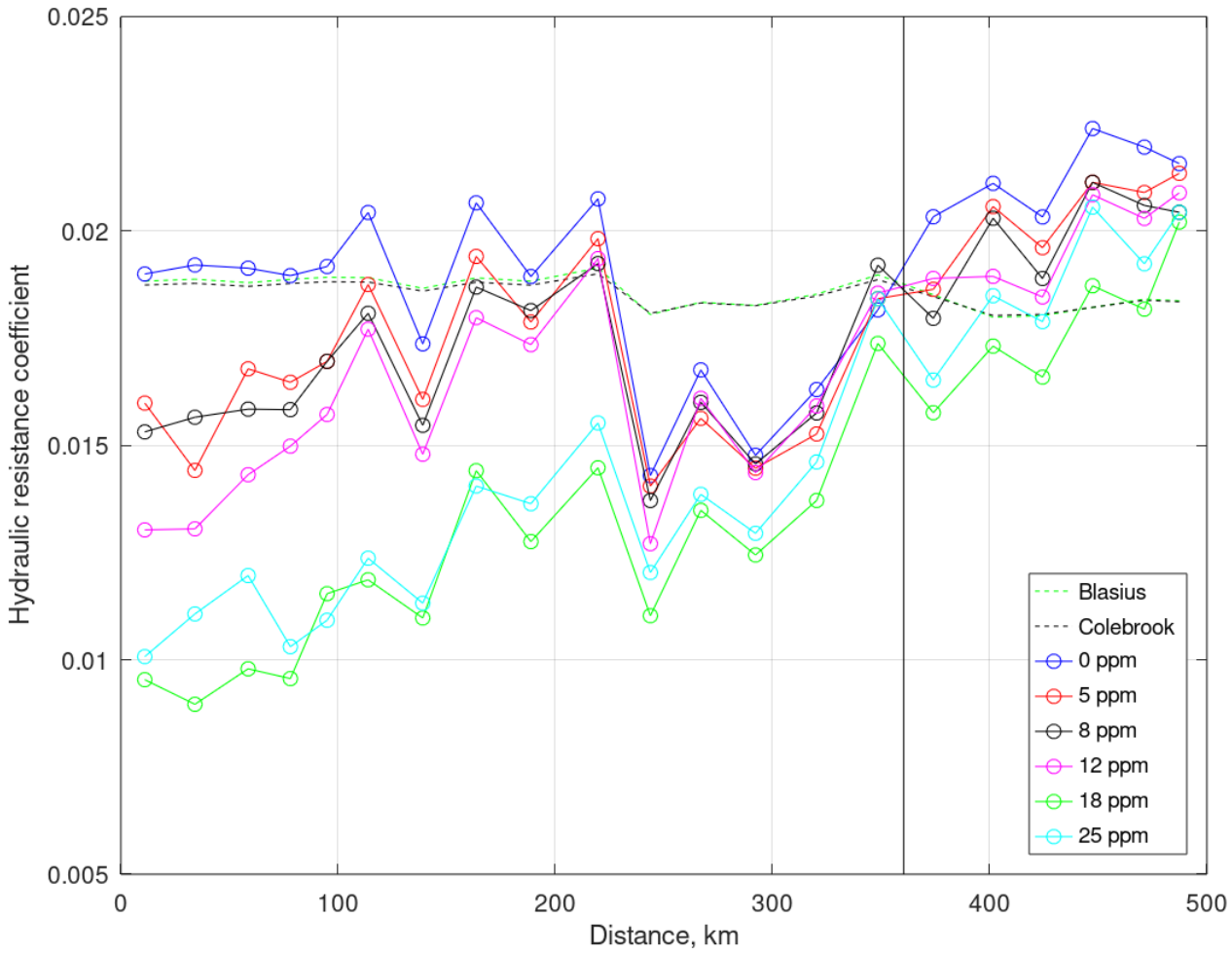


Figure 15 Hydraulic resistance coefficient distribution over travelled distance, Pipeline IV spring

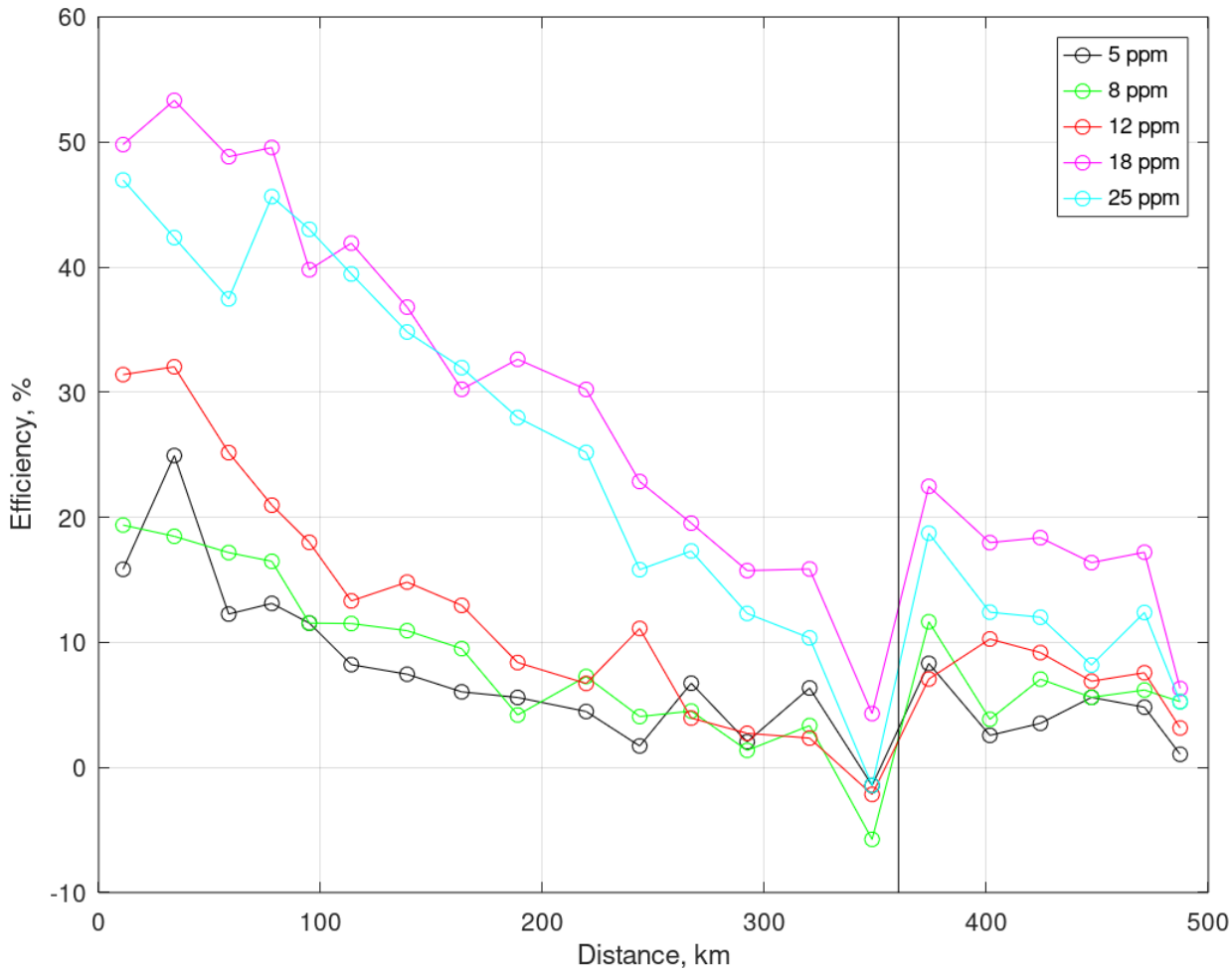


Figure 16 Efficiency distribution over travelled distance, Pipeline IV spring

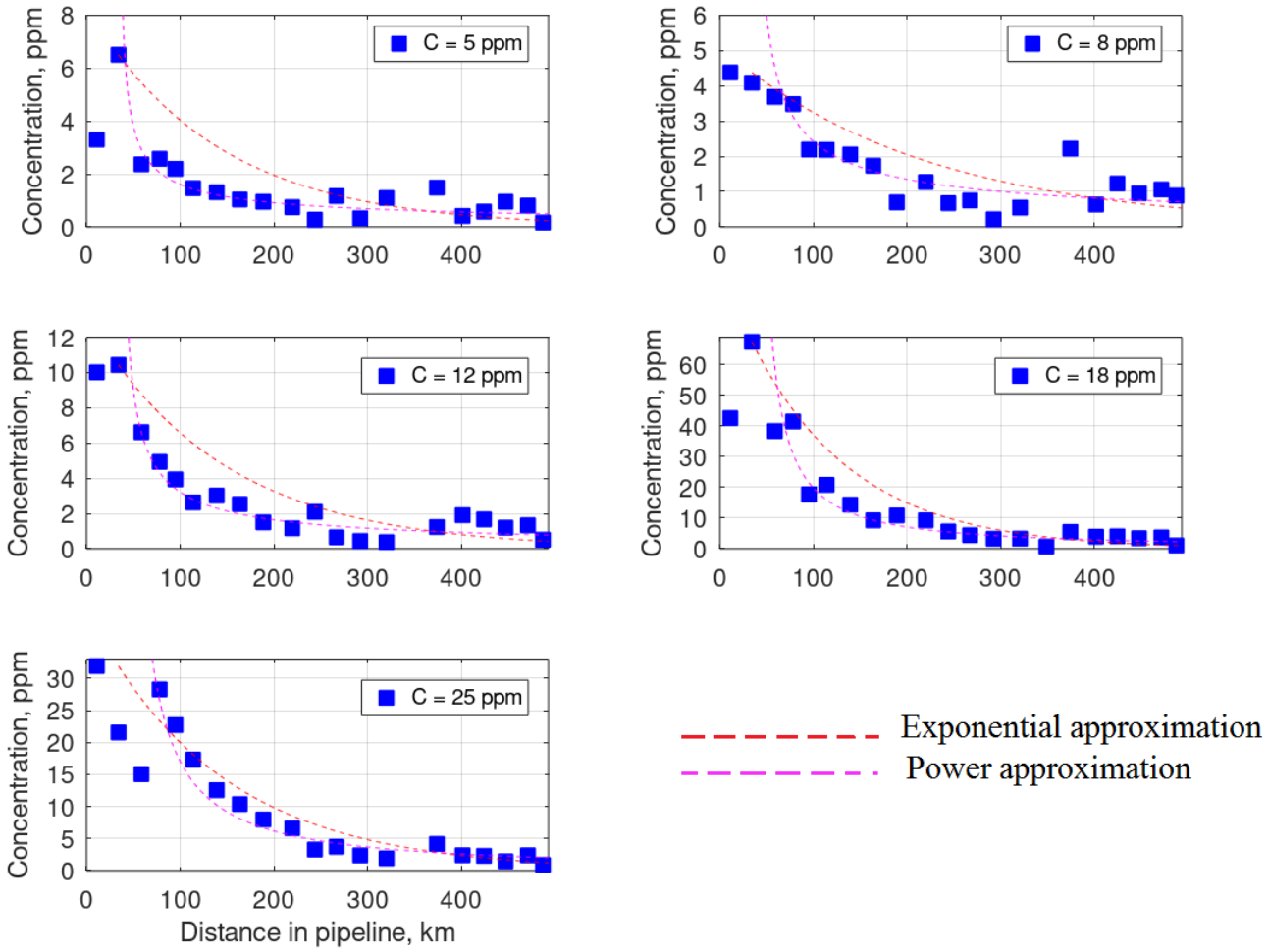
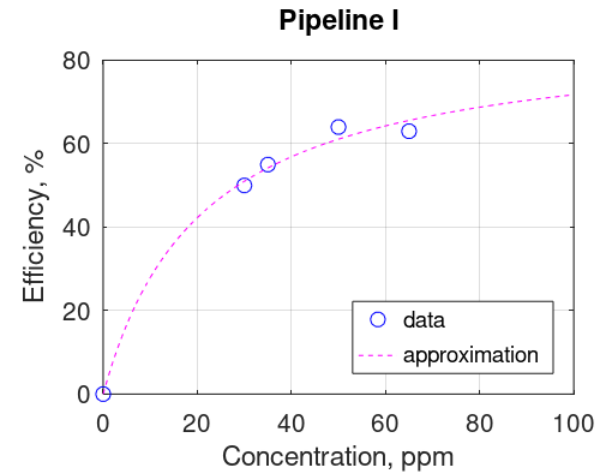
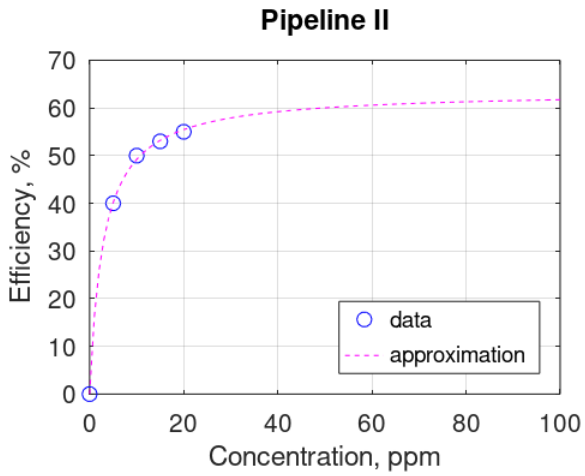
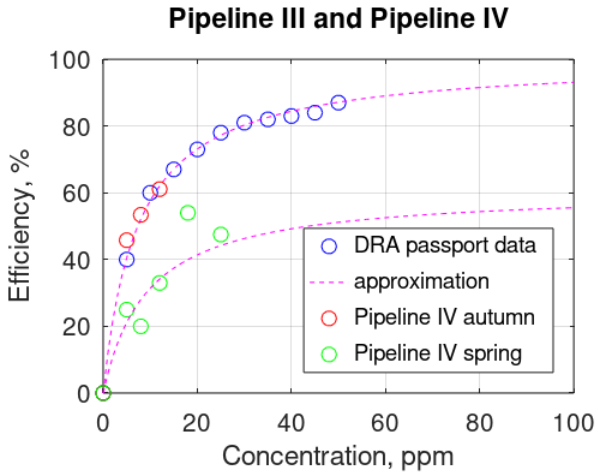


Figure 17 Concentration distribution over travelled distance, Pipeline IV spring







Characteristic values of oil properties for Pipeline IV

Pipeline IV	Spring	Autumn
Density, kg/m3	855	845
Viscosity, cSt	11-12	6 -7
Temperature, C	2 - 5	8 - 12

Figure 18 DRA efficiency as a function of concentration