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ANALYSIS OF THE FLOW OF CRYSTALLISING WATER SLURRIES IN PIPELINES

ANALIZA PRZEPŁYWU SZLAMÓW WODNYCH KRYSTALIZUJĄCYCH W RUROCIĄGACH

A b s t r a c t

The paper presents a method for monitoring the flow conditions in pipelines in the case of transport of crystallising water slurries forming scale. The method's core is the ability to calculate the equivalent pipeline diameter under varying flow conditions in industrial practice. The method was successfully tested in the laboratory and employed in an industrial plant.

Keywords: hydrotransport, formation of scale in pipelines, flow monitoring

S t r e s z c z e n i e

W artykule przedstawiono metodę monitorowania warunków przepływu w rurociągach w przypadku transportu krystalizujących szlamów wodnych tworzących osady. Sedno metody to przedstawienie sposobu obliczania średnicy zastępczej rurociągu w warunkach zmiennego przepływu w praktyce przemysłowej. Metoda została z powodzeniem przetestowana w laboratorium i wdrożona w jednym z zakładów przemysłowych.

Słowa kluczowe: hydrotransport, tworzenie się osadów w rurociągach, monitoring przepływu

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1. Introduction

Many branches of industry employ long distance pipeline hydraulic transport of waste powder solids. Because of a complex chemical composition of the transported solids, a partial solubility in water of individual components of the mixture, possible chemical reactions between them in the water environment and varying transport conditions caused by the weather, scale on the internal pipeline surface grows as a result of the crystallisation effect (Fig. 1). The problem of solid's deposition in pipelines is also discussed in the literature [1, 2, 3].

Fig. 1. A view of a pipeline cross-section – the formed scale decreases the free cross sectional area

As a result of the scale formation, the pipeline throughput decreases. In order to keep the flow rate of slurry at a constant level, it is necessary to gradually raise the inlet pressure generated by the pumps by increasing their rotational speed. In order to do this, a problem of gradual increase of the current intensity and a simultaneously higher consumption of power by pumps appears. It results in higher operational costs. Because of this, a lot of effort is put in industry to prevent the crystallisation and formation of scale in pipelines by adding carefully selected chemical agents.

In order to prove the effectiveness of the applied chemical additives, it is necessary to develop a continuous method for monitoring the flow conditions. But in industrial practice, the streams of transported slurries often vary in time intervals, which results in difficulties in making an appraisal. The authors made an effort to find a parameter to appraise the flow conditions in pipelines, i.e. an actual diameter, independent of the stream quantity. As a result of the investigations, an equivalent pipeline diameter derived on the basis of the Darcy-Weisbach equation has been introduced.

2. Analysis of flow conditions in an industrial plant

The analysis was carried out in an industrial hydrotransport plant susceptible to scale formation. The analysing operational parameters were:

- the discharge pressure values at the inlets to individual pipelines,
- the current intensity values received by pumps,
- the volume flow rate values of pumped slurry.

The analysis was based on a large range of data. They were systemised and averaged to cause their clarity.

The exemplary plots of pressure vs. time in a selected pipeline inlet, and the current intensity consumed by pumps vs. the time to keep a constant pump capacity in time in this pipeline are presented respectively in Figs. 2-4.

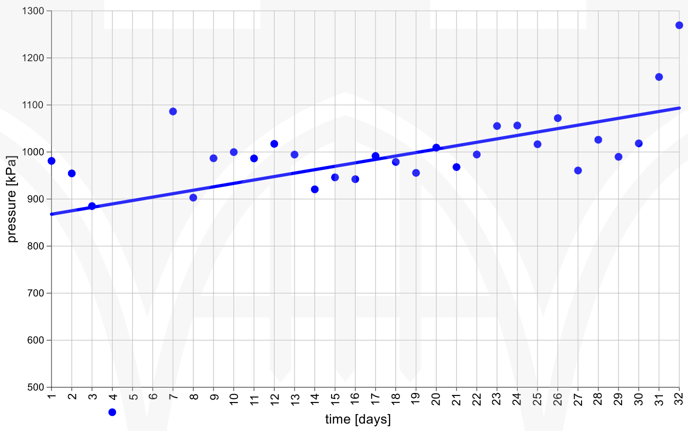


Fig. 2. Pressure vs. time for a selected pipeline

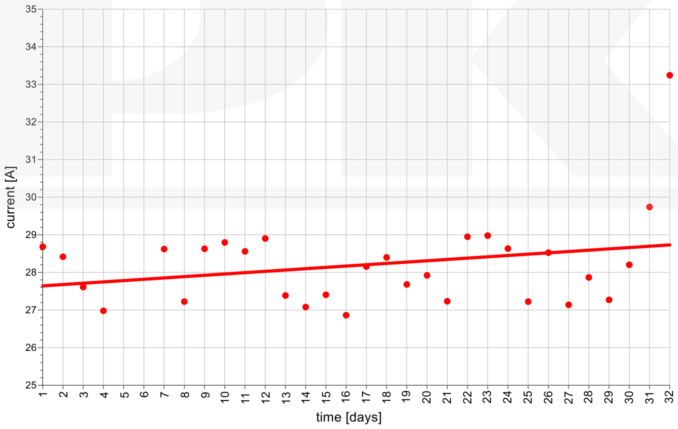


Fig. 3. Current intensity vs. time for a selected pipeline

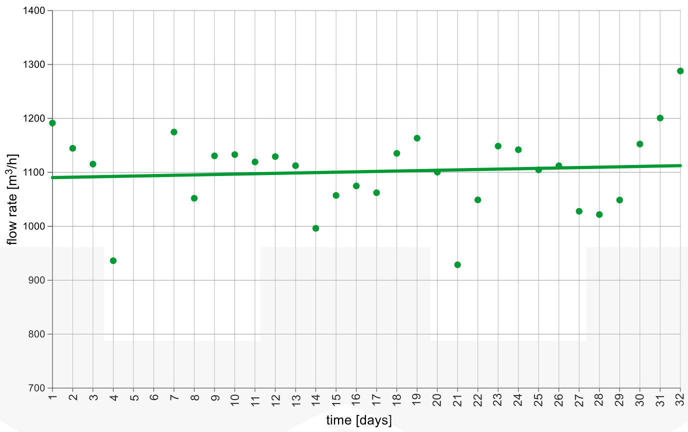
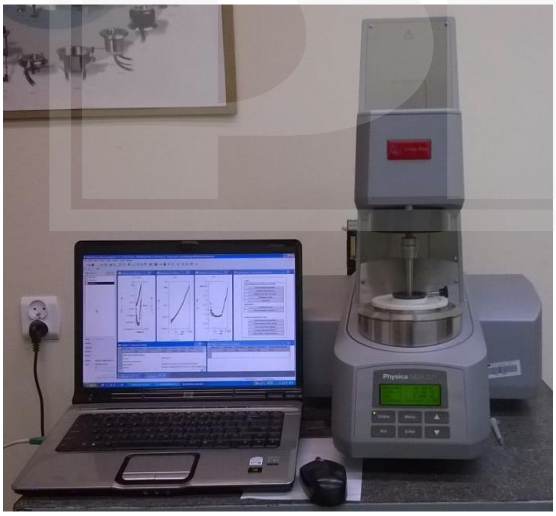


Fig. 4. Pump capacity vs. time for a selected pipeline

3. Rheological studies of examined slurry

Monitoring the hydrotransport pipeline, especially under conditions of various flow rates, demands the determination of the parameter unambiguously describing the pipeline's state, regardless of the flow conditions, such as the flow rate and the pressure drop. This parameter could be the dimensionless equivalent pipeline diameter.

To determine the dimensionless equivalent pipeline diameter using the Darcy-Weisbach equation, it is necessary to identify the rheological parameters of the flowing slurry, including the curves describing the flow resistance [4].



Technical Data	Unit	MCR 302
Bearing		Air
EC motor		Yes
Maximum torque	mNm	200
Min. torque, rotation	nNm	1
Min. torque, oscillation	nNm	0.5
Angular deflection (set value)	μrad	0.05 to ∞
Min. angular velocity	rad/s	10^{-9}
Max. angular velocity	rad/s	314
Max. speed	1/min	3000
Min. angular frequency	rad/s	10^{-7}
Max. angular frequency	rad/s	628
Normal force range	N	0.005-50
Normal force resolution	mN	0.5

Fig. 5. MCR301 rheometer with basic technical data

In order to identify the rheological parameters of the flowing slurry, the rheological studies were carried out with the application of a rotational rheometer (MCR 301 type) available at the Department of Fluid Mechanics. The rheometer and its basic technical data are presented in Fig. 5.

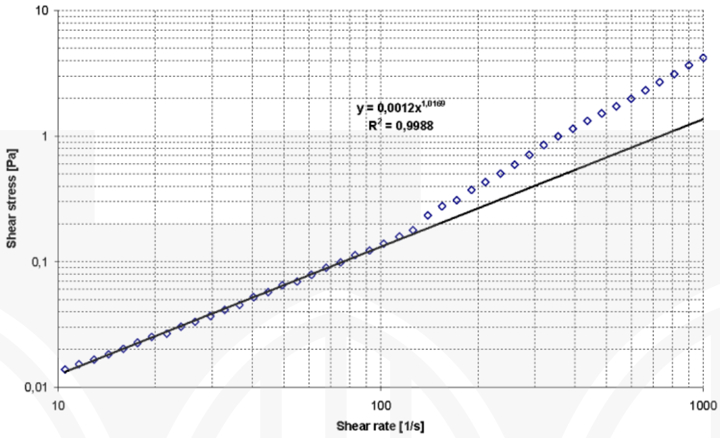


Fig. 6. Flow curve of slurry flowing through the examined pipeline

The prepared slurry was subjected to a preliminary rheological examination in order to determine the characteristics of its rheological parameters. The resulting flow curve with regression is shown in Fig. 6. This curve describes a relationship between the tangential stress and the shear rate. The values of the flow behaviour index *n* and the flow consistency index *K* according to Ostwald - de Waele rheological model were determined by linear regression of the experimental data and presented in the logarithmic scale.

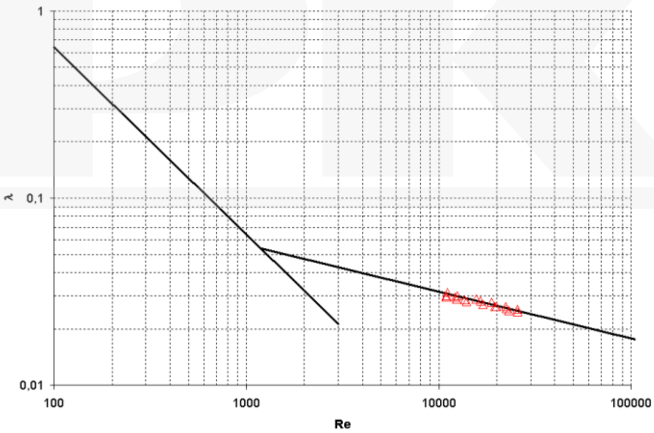


Fig. 7. Comparison of friction factor λ (measured – red, Blasius formula – black) in turbulent flow using a capillary-pipe rheometer

The obtained results of the flow behaviour index *n* for the tested slurry are close to 1, so the tested slurry can be treated as a Newtonian liquid and the flow resistance can be presented in classic Reynolds number (*Re*)-lambda (λ) layout.

The aim of further research was to determine the curve of flow resistance of the slurry flowing through the examined pipeline. The studies were carried out in a tube of an inner diameter D = 13.04 mm. The measurements were made with the application of a capillary-pipe rheometer built at the Division of Fluid Mechanics [5]. This setup allows to conduct a comprehensive identification of the rheological properties of complex rheological fluids in the laboratory. The test results are shown in Fig. 5.

4. Derivation of formula for calculating the equivalent pipeline diameter

The formula for calculating the dimensionless equivalent pipeline diameter can be derived on the basis of the Reynolds number formula and the Darcy-Weisbach equation:

$$Re = \frac{D \cdot u}{\nu} \tag{1}$$

$$\lambda = \frac{D \cdot \Delta p}{2 \cdot \rho \cdot u^2 \cdot L} \tag{2}$$

where

- D – the nominal pipeline diameter,
- u – the mean flow velocity,
- ρ – the density of slurry,
- ν – the kinematic viscosity coefficient of the slurry,
- Δp – the pressure drop in the pipeline,
- L – the pipeline length.

Basing on the resistance curve, it can be found that the Darcy friction factor λ in the turbulent flow can be approximated with the Blasius formula:

$$\lambda = \frac{0.3164}{\sqrt[4]{\frac{D \cdot u}{\nu}}} = \frac{0.3164}{\sqrt[4]{\frac{4 \cdot Q}{\pi \cdot D \cdot \nu}}} \tag{3}$$

where

- Q – the volume flow rate.

When replacing the mean velocity with the volume flow rate, the Darcy-Weisbach equation can be written as follows:

$$\Delta p = \lambda \cdot \frac{8 \cdot L}{D^5} \cdot \frac{\rho \cdot Q^2}{\pi^2} \tag{4}$$

Then, the friction factor λ can be described by the relation:

$$\lambda = \frac{\pi^2 \cdot \Delta p}{8 \cdot L \cdot \rho} \cdot \frac{\cdot d^5}{Q^2} \tag{5}$$

where

d – the actual pipeline diameter related to the free cross-sectional area.

When equalising (3) and (5) and taking into account the actual diameter, a following relation can be obtained:

$$d = \left(3.398 \cdot 10^{-3} \cdot L^4 \cdot \rho^4 \cdot \nu \cdot \frac{Q^7}{\Delta p^4}\right)^{\frac{1}{19}} \tag{6}$$

For a fluid flowing through a pipeline, it can be assumed that the values in equation (6) are constant, except for the volume flow rate *Q* and the pressure drop *Δp*. Hence, the dependence (6) can be represented as:

$$d = B \cdot \left(\frac{Q^7}{\Delta p^4}\right)^{\frac{1}{19}} \tag{7}$$

where

B – the constant describing the liquid and the pipeline parameters.

The dimensionless equivalent pipeline diameter d_e has been defined as a ratio of the actual pipeline diameter *d* to the nominal pipeline diameter *D* (it is a relative quantity):

$$d_e = \frac{d}{D} \tag{8}$$

5. Results and discussion

The developed method for determining the dimensionless equivalent pipeline diameter has been applied for monitoring the bore of a selected industrial pipeline. An additional object of monitoring was a verification of the effectiveness of the action of chemical additive preventing crystallisation and scale deposition in the pipeline. The composition of the chemical additive is confidential. Earlier, during the hydrotransport, the examined pipeline grew over with scale and it was necessary to clean it periodically.

The tests proved the correctness of the developed method of pipeline monitoring: it indicated a gradual decrease of the dimensionless equivalent pipeline diameter (Fig. 6 left – a declined line with time) in normal operation. The application of the mentioned chemical additive caused a set-back of the crystallisation and scale deposition in the pipeline (Fig. 6 right – the horizontal line, a constant value of the dimensionless equivalent pipeline diameter).

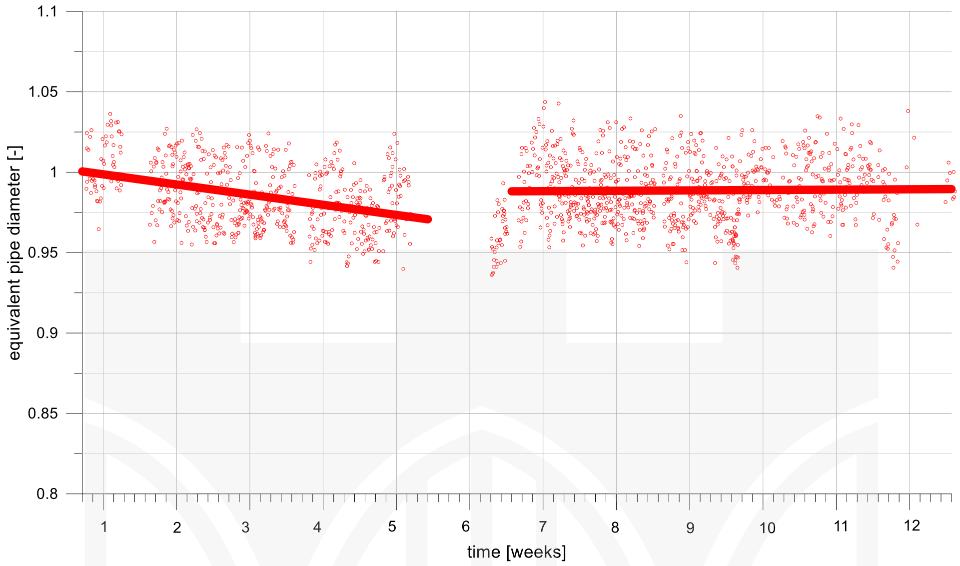


Fig. 6. The results of tests of the hydrotransport pipeline dimensionless equivalent diameter (a linear approximation)

The presented method can be applied in industrial practice for monitoring the bores ofpipelines in case of varying flow rates.

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