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Assessment of Slurry Transport Efficiency after Applying Deflocculant in the Lime Production Process

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Abstract
The paper presents a method for improving the lime production process by increasing the efficiency of the lime slurry transport that occurs in it. The aim of the study was to reduce the energy demand of the pump installed in the discharge line. The presented solution consists of applying an additive called deflocculant to the transported slurry in order to reduce its viscosity while increasing the concentration of solids content. The deflocculant applied to the slurry is composed of waste material from the lime slaking process and an environmentally neutral chemical substance in the form of sodium-water glass. The rheological studies conducted confirm the positive effect of the selected deflocculant on the properties of the slurry tested. As a result of the analysis, it has been shown that the proposed solution has a substantial effect on reducing the friction factor of the transported slurry, thus reducing the energy consumption in the investigated process.

Keywords
Efficiency; Lime production process; Deflocculant; Friction factor; Energy savings.

Introduction

Efficiency is defined as a positive result, effectiveness or the result of economic activity understood as the ratio of the achieved effect to the input. An efficiency improvement programme is a complex technical and organisational effort carried out to evaluate the activity of the entire company or its smaller areas (Drabik and Sobol, 2016).

The concept of efficiency is most commonly associated with the concept of rational management and is defined in two ways (Knosala, 2017): efficient (productive), where the goal is to maximise effects and cost savings, minimising inputs.

The measure of the effectiveness of an organisation's operations is its productivity. Productivity expresses the relationship between the goods and services produced and the resources used to produce them (Christopher and Thor, 1993).

There are three approaches to productivity (Goshau et al., 2017): technical, expressed as the relationship between the output and the inputs used in production, engineering, expressed as the relationship between the actual and potential output of the process, and economic, expressed as the efficiency of the resources.

Figure 1 shows a diagram of the technical concept of productivity. In the presented diagram, the technical concept of productivity is expressed as the ratio of the amount of output produced and sold during the period of time analysed relative to the amount of input resources used during that period.

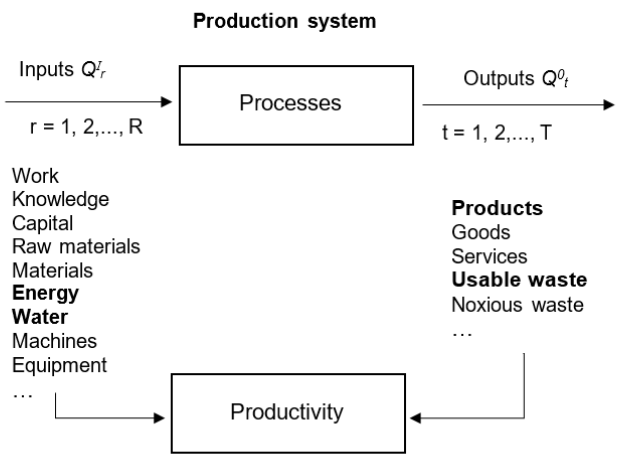

Fig. 1. Technical concept of productivity (Knosala, 2017)

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Mathematically, productivity (P_i) is described by an equation (Kosieradzka, 2012):

$$P_i = \frac{\sum_{t=1}^{T} Q_{ti}^{O}}{\sum_{r=1}^{R} Q_{ri}^{I}} \tag{1}$$

where the numerator contains the volume of production and the denominator the amount of input incurred. Companies usually seek opportunities to increase their productivity by increasing the value of outputs achieved or by reducing the value of inputs incurred in production (Bozarth & Handfield, 2006).

In the analysed process of lime production, materials and intangible resources used in the production and considered as the inputs of the production system include: limestone, water and electricity used to drive machines in the flow installation. The outputs of the production system are processed limestone and by-products of the production process which constitute useful and harmful waste. They are mainly lime slurry, calcareous groats and residues from the lime slaking process.

The lime production process generates significant amounts of waste in the form of sand and dusty solid particles, which result from the washing of lime stone. These particles are continuously transported by pipeline, using water as the carrier liquid, to industrial ponds. The available data indicate that the particles are transported in low concentrations, so the hydrotransport process requires the use of a large amount of electricity to power the centrifugal pump. Therefore, a solution is proposed to increase the concentration of the solids in the slurry transport process after the application of a deflocculant. The addition of a deflocculant of a specific composition contributes to the reduction of the viscosity and shear stress of the slurry, as well as to the reduction of the sedimentation process during flow in a pipeline (Senapati et al., 2009). This makes the hydrotransport process more predictable (less fluctuations in pressure and flow rate) and less prone to the risk of "plugging" the pipeline when transport is stopped and then resumed, e.g., due to pump failure or temporary power failure. This should result in an increase in the economic viability of the applied solution.

In the paper, the efficiency of the transport of slurry in the lime production process is considered as the ability to pump a given amount of solids in a given unit of time relative to the amount of electricity required to drive the centrifugal slurry pump.

The presented approach is part of the concept of continuous improvement, according to which small cumulative improvements can increase the efficiency of the entire process over time. Continuous process improvement is one of the key tasks of effective business management.

Literature review

In industrial plants, there is an increasing demand for pumping slurries consisting of finer particles at increasing concentrations. In limestone processing, the fineness of the particles increases as a result of grinding the stone and saturating the solution with dust particles from this process. This increases the effect of particle concentration on the properties of the overall slurry resulting from interactions between particles, e.g. as a result of van der Waals and electrostatic forces. This phenomenon results in changes in the rheological parameters of the slurry (Parzonka et al., 1981; Shook and Roco, 1991), and (Chhabra and Richardson, 2008).

Slurry transport in pipelines is an established technology in the mining and mineral processing industry. Most researchers in slurry pipeline transport are concerned with predicting pressure loss, or determining the minimum conveying velocity (deposition velocities) for safe transport and on the impact of solids loading, particle shape, and rheology on pressure gradient (Wu et al., 2010).

To minimise the proportion of the carrier phase in the pipeline transport of a two-phase mixture, additives called deflocculants are often used. A deflocculant, which belongs to the group of drag reduction agents (DRAs), is a chemical compound designed to repel suspended particles from each other, resulting in dilution and allowing proportionately more solids to enter the slurry. The addition of a deflocculant at a fraction of a percentage by weight of the solid phase of the transported slurry results in a significant reduction in friction as an effect of changing the rheological properties of the slurry from non-Newtonian to Newtonian (Lumley, 1969; White and Mungal, 2008). The addition of a suitable deflocculant to the slurry results in a significant reduction or even elimination of the yield stress, allowing an increase in the concentration of solids contained in the slurry (Matras & Kopiczak, 2016; Kaushal et al., 2018; Rajappan and McKinley, 2020).

The first report of drag reduction during slurry transport in pipelines in the mining and mineral processing industry dates to the 1950s by Toms (1948), who found that the pressure drop of carrier liquid with the addition of polymers was lower than without it. However, Forrest and Grierson (1931) and Brautlecht and Sethi (1933) discovered that the addition of dilute suspensions can reduce the friction in the pipe when pumping paper pulps. For many years, the phenomenon of pressure drop reduction after the addition of drag reduction agents did not receive much attention from scientists, until the beginning of the 1990s, when Nadolink and Haigh, (1995) summarised the number of publications including journal articles, technical reports, book chapters, and conference papers about drag reduction by additives. Increasing interest in this topic was assumed probably after the de Gennes's Nobel Prize lecture in 1991 (De Gennes, 1992), who defined the concept of a complex fluid that works for drag reduction by polymers. Since then, addiditives, called in the literature as deflocculant or drag reduction agents, because of their potential practical use, have become the subject of much interest in various branches of industry and scientific works. In the literature, the pressure losses data during flow of slurries in pipelines are presented in order to determine the power consumption required in selecting and sizing slurry pumps, and to optimise the pipeline design parameters (e.g. pipe diameter, percentage of fine particles) so as to minimise the capital cost and energy consumption (Schaan et al., 2000).

The solution proposed in the present study is to add a deflocculant composed of sodium water glass and post-hydration porridge to the washing water mixture to significantly reduce drug reduction (Jaworska-Jóźwiak & Dziubiński, 2022). The added substances are intended to disperse the hydromixed particles as a result of the breakdown of the particle aggregates, reducing the shear stresses created in the particles. This would allow the transport of a slurry with a high concentration of solids. The addition of deflocculant lowers the critical flow velocity and reduces the formation of bottom deposits in the flow system (Chipakwe et al., 2020; Mingzhi et al., 2022).

From the point of view of the productivity improvement in the analysed production plant, the most important benefits resulting from the application of deflocculant in slurry flow are (Jubran et al., 2005):

- increased pipeline capacity,
- savings in pumping power,
- flow pressure reduction with the associated reductions in pipe thickness,
- limitation of the number of flow facilities,
- decrease in the diameter of the pipe in the design phase.

The other advantage of the deflocculant application is also the possibility of immediate or temporary implementation, which results in high operational flexibility (Zhang et al., 2021).

Materials and methods

In the study, the results of the calculations of the energy consumption during the flow of the tested slurry in a pipeline after the addition of a selected deflocculant are presented. An experimental and simulation study of the effect of a deflocculant, containing a waste substance generated in the lime production process and an environmentally neutral substance, on the viscosity of a slurry with four different mass concentrations was carried out. The composition of the proposed deflocculant was self-developed and determined by experimental studies performed according to the experimental design method.

In the first step of the investigation, rheological measurements of the slurry tested after the application of the deflocculant were performed. The slurry sample subjected to experimental tests was taken from the industrial installation of the production plant. It is the wash sludge, known as a 'slurry', which is the medium transported in the final stage of the lime production process. The solid fraction consists of fine particles of the quarried stone, which contain a high proportion of calcium carbonate (74%) and silicon dioxide (13%). Figure 2 presents an image of the dried lime slurry made with a Phenom Pro X scanning electron microscope (SEM) after applying a 10 kV electron accelerating voltage.

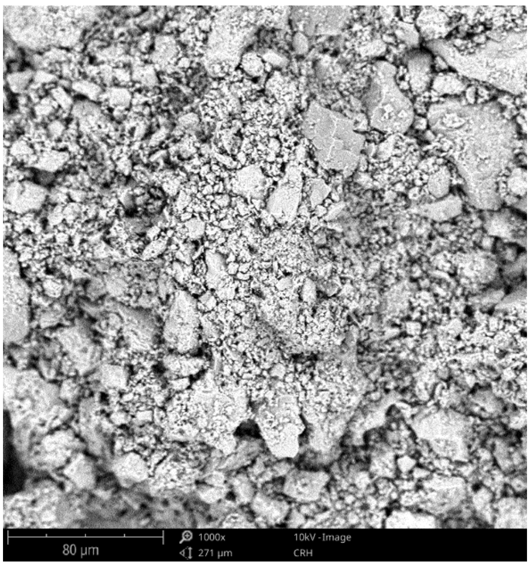

Fig. 2. Dried lime slurry sample made by SEM with 1000 magnifications

Experimental studies of the slurry were carried out in the slurry density range of approximately 1140 kg/m^3 to 1410 kg/m^3, corresponding to a mass concentration of 21.30% to 50.00%. Slurry rheological tests were performed using an Anton Paar MCR 302 rotational viscometer. The density of the carrier, which was water, was 998.2 kg/m^3, while the density of the solid phase was 2400 kg/m^3.

A deflocculant consisting of sodium water glass and lime porridge, known as 'calcareous groats', was added to the slurry to measure viscosity. The measurements results showed that the addition of the proposed deflocculant has a positive effect on improving the rheological properties of the tested slurry. It manifests itself in a reduction in the viscosity of the slurry after application of the deflocculant (Fig. 3). At the same time, the addition of the deflocculant reduces frictional losses during the flow of the slurry in the pipeline.

In the second part of the study, the amount of electricity required to drive the centrifugal pump transporting the slurry in one hour was determined. The necessary calculations were made for a basic slurry without the addition of deflocculant (C_m = 21.30% pure) and for slurries with mass concentrations of 28.14%, 35.00%, 42.75% and 50.00% with the addition of deflocculant.

Results

Calculations of the energy demand of the motor driving the centrifugal pump during slurry transport in a pipeline were carried out under industrial conditions, i.e. with a solid phase concentration of C_m = 21.30% and a volumetric flow rate of Q_v = 110 m^3/h. The calculation results were compared with those for slurries with mass concentrations of 28.14%, 35.00%, 42.75% and 50.00% with the addition of deflocculant. According to current plant needs, it was assumed that the dry mass of the solids in the slurry, transported in 1 hour, should be 27 t.

Table 1 presents the parameters that characterise the slurry, when a constant amount of the solid phase mass is transported.

In Table 1, the slurry with the addition of deflocculant is denoted as +DFL, while the base slurry without the addition of deflocculant is denoted as pure.

The power on the pump shaft (P_w) is the power consumed by the pump, equal to the mechanical power

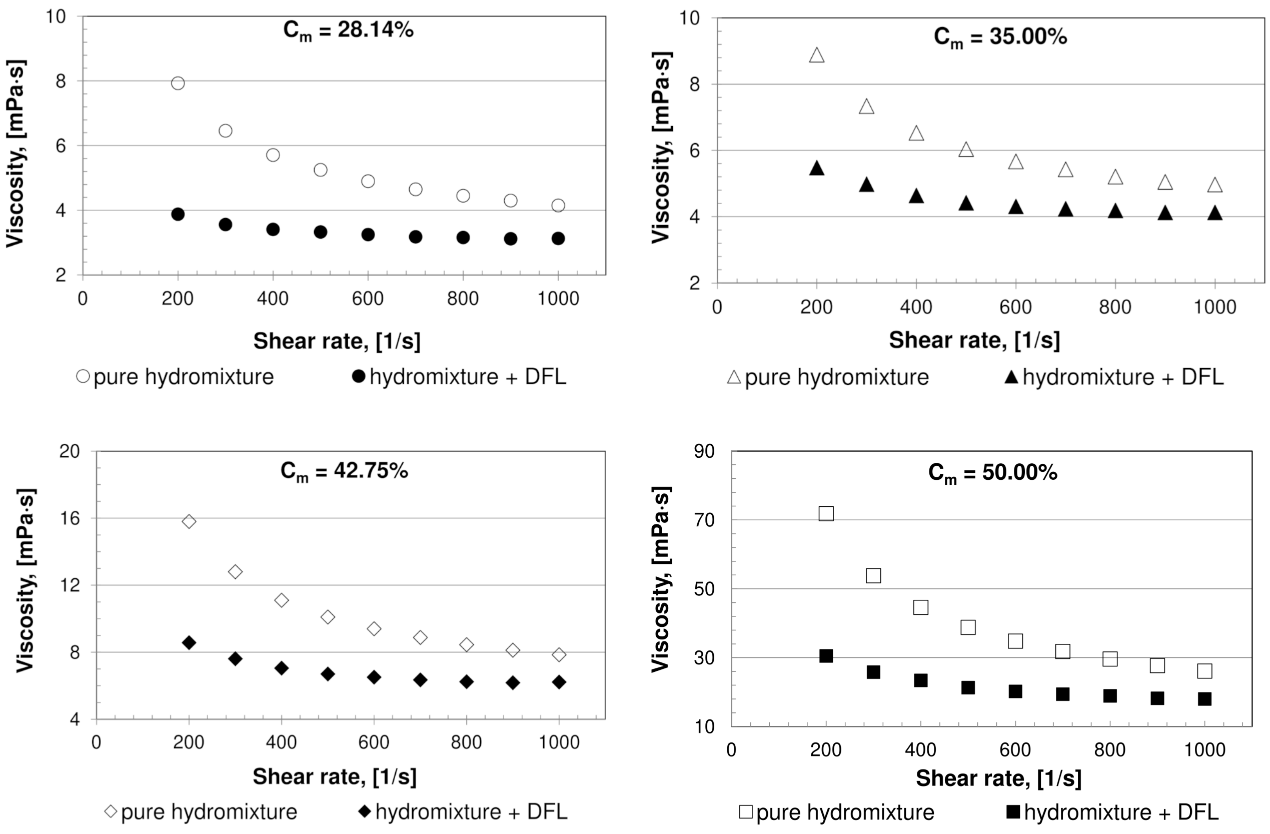

Fig. 3. Experimental viscosity curves of the slurries tested with the addition of deflocculant

Table 1
Selected parameters characterising the slurry in the hydrotransport process

C_m, %	Q_v, m^3/h	Δp, Pa	γ, N/m^3
21.30 pure	110	144 480	11 185
28.14 + DFL	80	141 749	11 719
35.00 + DFL	61	144 327	12 307
42.75 + DFL	48	153 050	13 051
50.00 + DFL	38	189 286	13 830

provided by the drive motor. This value is obtained indirectly by measuring or calculating the power consumption of the electric motor (Ps) driving the pump (Siwek, 2017):

$$P_w = P_s \cdot \eta_s \tag{2}$$

where η_s is the efficiency of the pump motor.

Based on assumptions of the physical properties of the slurries, the power on the pump shaft of the slurry flow in the tested pipeline was calculated from the expression:

$$P_w = \frac{\gamma \cdot Q_v \cdot H_p}{\eta} \tag{3}$$

where γ is the specific gravity, Q_v is the volumetric flow rate, H_p is the pump discharge height and η is the pump efficiency.

The slurry flow pressure drop (Δp) was determined from the equation:

$$\Delta p = \gamma \cdot H_p \tag{4}$$

In the calculations of the power on the pump shaft of the slurry flow, the pump efficiency is assumed to be 62%, which corresponds to the data provided by the manufacturer of the equipment used in the considered production plant. The results of the calculation are presented in Table 2.

Table 2
Power on the pump shaft required to pump the slurry with selected mass concentrations

C_m, %	21.30 pure	28.14 + DFL	35.00 + DFL	42.75 + DFL	50.00 + DFL
P_w, W	7120.48	5080.61	3944.42	3291.39	3222.63

Knowing the efficiency of the electric motor driving the pump at 75% load equal to $\eta_s = 93.6\%$, it is possible to determine the amount of electricity consumption required to pump the slurry with the transport parameters given from Eq. (2).

The measure of the effectiveness of slurry addition (drag reduction agent – DRA) in reducing the friction factor during flow of slurry in a pipeline is defined by (Jubran et al., 2005):

$$\text{effectiveness}(\varepsilon) = \frac{\Delta P_{\text{without DRA}} - \Delta P_{\text{with DRA}}}{\Delta P_{\text{without DRA}}} \tag{5}$$

Figure 4 presents a summary of the power consumption of the pump motor (P_s) when transporting the slurries with the addition of deflocculant. In the graph, the filled markers represent the power consumption of the pump motor when pumping slurries with different mass concentrations, while the empty markers represent the energy consumption effectiveness calculated from equation (5).

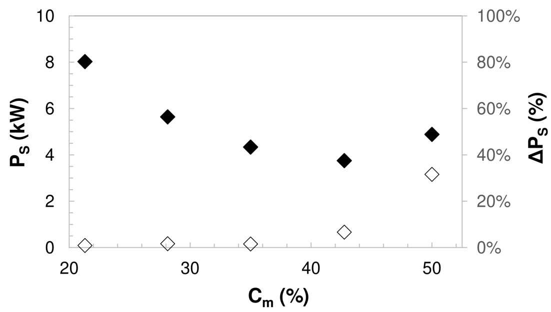

Fig. 4. Consumption of electric power of the centrifugal pump motor during the transport of slurries

From the graph presented, it can be concluded that the electricity consumption by the motor driving the centrifugal slurry pump when transporting slurries of various mass concentrations with the addition of deflocculant decreases in the presented range of the shear rate despite the significant increase in the mass concentration of the slurries. This effect is the result of a decrease in the viscosity of the slurry after the application of the selected deflocculant. In each case, a constant amount of solids is pumped, equal to 27 t during 1 h.

Discussion

The solution presented in this paper is to apply a deflocculant to the lime slurry flowing in the pipeline, which significantly reduces its viscosity and allows its mass concentration to increase. As a result of the reduction in viscosity of the slurry obtained after the application of the deflocculant, the necessary amount of electrical energy to pump the medium with various mass concentrations is reduced. For the same amount of mass of the transported solid phase of 27 t, the estimated amount of electricity consumption for a slurry with a mass concentration of 42.75% and 50.00% (more than twice as high as the base concentration) with the addition of deflocculant is approximately 54% lower than the amount of electricity consumption when pumping a base slurry without the addition of deflocculant ($C_m = 21.30\%$ pure).

The effectiveness of drag reduction agents, to which deflocculants are included, is affected by several factors, such as the diameter of the pipe in the industrial installation, the temperature and viscosity of the flowing slurry and the presence of water (Wu et al., 2010). The efficient use of water and energy in long-distance slurry pipelines is analysed including the total cost function resulting from an energy and mass balance. In connection with the additional and recurrent constraint caused by mining operations and water scarcity, the problem of energy efficiency has been recast as a problem of minimisation of the transport costs of the slurry (Ihle, 2016). In the presented analysis, the calculated measure of the effectiveness of deflocculant addition (DRA) in the reduction of the friction factor during the flow of slurry in a pipeline is growing with simultaneous increase in the mass concentration of solids and is approximately 30% for slurry with the highest tested mass concentration equals 50.00% (Fig. 4). This result is consistent with data presented in the literature, mostly orientated toward reducing energy consumption during the flow of liquids in conduits. Pullum & McCarthy (1993) compiled specific energy consumption data from a total of 20 publications, and they concluded that a high concentration of particles mixed in non-Newtonian viscous carrier fluids (such as fly ash and lime slurry), where solids concentration is typically more than 40% by volume, can be hydraulically conveyed at lower velocities with specific energy consumptions than those required for conventional dilute solids phase systems. Energy consumption at a suitable solid concentration during fluid transport through pipelines can be significantly reduced (Wu et al., 2010). Drag reduction agents (DRAs) can reduce pumping energy requirements by 50–70%. The effectiveness depends on the types of additives used and the pipeline system. Savings by DRAs are greater if the pipeline has fewer branches or the pipelines are longer or the number of fittings, such as valves and elbows, is relatively small (Wang et al., 2011).

The presented results of the rheological measurements and DRA – effectiveness calculation clearly demonstrate the benefits of applying deflocuant that resulted in an increase in the efficiency of solid phase transport in a lime – producing enterprise. The described solution indicates how a company can organise its operations in order to introduce improvements in the production process. Improving the rheological properties of the lime slurry with the addition of a suitable deflocculant increases the productivity of the hydrotransport process by decreasing the use of water and energy consumption.

The positive effect of the use of a deflocculant in the transport of the slurry complies also with the definition of economic efficiency, according to which the greatest efficiency or resource savings should be sought (Grudzień & Osiński, 2022). In the lime-producing enterprise analysed, this measure refers to achieving measurable results at the lowest possible cost, as well as achieving the highest possible result from a given number of inputs. In addition, the company improves its ability to use its resources productively to achieve its planned objectives, which is particularly important under conditions of economic volatility.

The concept of organisational effectiveness, which is dominant in the theory of management, also referred to as the effectiveness of the functioning of the system, concerns the company's ability to adapt to changes in the environment on an ongoing and strategic basis and to use its resources productively to achieve the planned goals. The solution presented in the paper is a response to the urgent need to look for energy savings in the current operations of production enterprises and to save water consumption, the resources of which during a hydrological drought are very limited.

Conclusions

The paper presents a method for improving the transport of slurry in a pipeline located in a limestone processing plant. The method consists of the use of the addition of a deflocculant, composed of waste material, in the transport of slurry in a lime production process. This resulted in considerable efficiency in its operations by reducing the use of individual production factors such as water and energy consumption.

The positive impact of using a deflocculant in the transport of the slurry translates into an increase in the efficiency of the entire production process. The reduced amount of process water that circulates in the production cycle also results in savings on earlier elements of the operation of the industrial plant, which were not included in the analysis presented. The application of the proposed solution also results in a reduction in the degree of pollution of industrial ponds (settling tanks), which is a measurable environmental effect.

Acknowledgements

Rheological studies were performed using an Anton Paar MCR 302 rotational viscometer in the Rheological Testing Laboratory at Kielce University of Technology.

The image of the dried lime slurry was performed using a scanning electron microscope integrated with an energy-dispersive X-ray spectrometer (EDS) at the Institute of Physics of the Silesian University of Technology.

Nomenclature

C_m	solids mass concentration, %
H_p	pump discharge height, m
t	$t = 1, 2, \ldots, T$ – number of products manufactured by the production system
P_i	a measure of the productivity of the production process
P_s	power consumed by the electric motor that drives the centrifugal pump, W
P_w	power on the centrifugal pump shaft, W
ΔP	power reduction in the pump shaft, W
r	$r = 1, 2, \ldots, R$ – number of types of resources used in the production system
Q^I_{ri}	quantity of input resource (I – input) of type r consumed during period i in the production system
Q^O_{ti}	quantity of products (O – output) of type t produced and delivered to customers during period i in the production system
Q_v	volumetric flow rate of the slurry, m^3/h
γ	Specific gravity of the slurry, N/m^3
Δp	pressure drop in the slurry flow, Pa
η	pump efficiency, %
η_s	pump motor efficiency, %
ε	DRA performance effectiveness, %

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