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IMPROVEMENT OF SLUDGE ELECTRODEWATERING BY ANODE FLUSHING

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Abstract

An improvement of the sludge electrodeewatering process is proposed: the anode flushing by filtrate recirculation. According to this technique, the mixture of filtrates obtained at cathode and anode sides, is used for continuous flushing of anode chamber of the filter press during electrodeewatering. The anode flushing is aimed to eliminate essential problems of electrodeewatering: ohmic heating, rise of electric energy consumption, electrodes corrosion, and filtrate contamination. This is attained by better control of the filtrate pH, the filter cake temperature and the dryness at anode side, where the physicochemical conditions are most aggressive.

The efficiency of the proposed technique is evaluated at lab scale on drilling sludge electrodeewatering with and without anode flushing. In experiments without anode flushing, increasing of electric current density caused strong increase of anode temperature, desiccation of the filter cake at anode side, rise of voltage and significant alkaline contamination of filtrate. The application of anode flushing allowed controlling the electric field strength and the temperature. Thus, the dewatering of the sludge has been extended at high electric field without damaging the filter equipment by drastic

heating. Furthermore, it reduced the filtrate contamination by neutralization of the electrolysis products.

KEYWORDS: Electro-dewatering, dead-end electrofiltration, filter press design, anode flushing, filtrate recirculation, Ohmic heating, drilling sludge

NOMENCLATURE

C_{∞}	ultimate filter cake dryness (wt.%)
C_{av}	average dryness of sample in filtration cell during dewatering (wt.%)
C_c	average filter cake dryness (wt.%)
E	local electric field strength (V/cm)
I	electric current strength (A)
i	current density (A/m ²)
J	filtrate flux (m/s)
P	electric energy (J)
Q	Joule heat (J)
R	electric resistance (Ohm)
S	cross sectional area of filter cell (m ²)
t	time (s)
U	voltage (V)
V	filtrate volume (m ³)
V_{cell}	inner volume of filtration cell (m ³)
W	specific energy consumption (kWh/kg of supplementary extracted filtrate)

α_{av}	specific cake resistance (m/kg)
ρ_l	density of liquid (kg/m ³)
ρ_s	density of solid (kg/m ³)
ϕ	average volume fraction of solid in filtration cell (dimensionless)
ϕ_0	volume fraction of solids in initial sludge (dimensionless)

1. INTRODUCTION

Sludge dewatering remains a technological and economic issue for many industries, including water treatment, construction, mineral, chemical, paper and food industries. Sludges, mineral or biological, contain high amount of water, which is difficult to eliminate by mechanical methods of solid-liquid separation. As a result, the high residual water content accounts for high costs of transport and disposal, or additional thermal drying of insufficiently dewatered sludge.

For example, the construction industry generates a large amount of drilling sludge (discharged drilling fluid) that contains about 20 wt.% of bentonite clay in combination with salts, dispersants and viscosifiers [1]. The fine size, high layer charge, large specific surface area of dispersed bentonite particles ensure particular property of drilling fluid to retain water in order to maintain stable drill holes. However, this also impedes the dewatering of drilling sludge by conventional mechanical methods (filtration-consolidation, centrifugation) [1,2].

Flocculation and aggregation are currently used to increase sludge particle size and thus to improve the filtration rate [3–5]. However, the application of flocculants may be undesirable, when it results in chemical contamination of the filtrate and filter cake, or reduces the final cake dryness [2]. On the one side, these problems provoke the interest to the application of environmentally friendly flocculants [6,7]. On the other side, this encourages the elaboration of alternative methods of sludge dewatering [5, 8–13].

1.1. Sludge Electrodewatering

The electrodewatering implies the application of an electric field that generates direct electric current in the sludge during the mechanical separation process (generally, during filtration-consolidation) [14]. Electric field generates movement of ions and charged particles (electroosmosis and electrophoresis) that can reduce particles accumulation on the filtering media, accelerate the filtrate flow through the filter cake, and thus increase the dewatering rate. As pointed out by Weber and Stahl [15], the potential of the electrically assisted separation increases with the particle surface area, when the efficiency of simple mechanical dewatering processes decreases.

As demonstrated in a number of experimental investigations performed at lab scale since the nineties, the application of pressure in combination with direct electric current seems to be an interesting alternative to mechanical sludge dewatering [9, 10, 13, 16]. It was shown that electrodewatering of model bentonite suspensions as well as real drilling sludges results in higher filtrate flux and final cake dryness, as compared to the pressure

filtration-consolidation alone, while the energy consumption during the electrodeewatering is lower as compared to that required for thermal sludge drying [2, 17, 18].

The electrodeewatering technology has been adapted for existing industrial mechanical processes, such as plate or diaphragm filter press [19–23], belt filter [24–27], and rotary drum filter [28]. Pilot scale studies have confirmed the efficiency and technical feasibility of the electrodeewatering [21].

However, the electrodeewatering technology is not commonly used in industry. There are several issues that hampered its practical realization and commercialization: (1) significant risk of ohmic heating, (2) high electric energy consumption at terminal stages of the dewatering, (3) alkalization and acidification of filtrate and filter cake due to the electrolysis reactions, and (4) electrode corrosion. These problems are fundamental for any kind of electrodeewatering process, since they are caused by the fact of electric current passage through the sludge.

1.2. Ohmic Heating

The application of an electric field inevitably causes filter cake's ohmic heating that increases with the electric field strength and the electrical resistance of the system. From the one side, the heating decreases the filtrate viscosity that has to accelerate the filtrate flow [15]. From the other side, the uncontrolled heating may damage the filter cloth and filter plates.

Lee et al. [22] investigated the sludge electrodeewatering at pilot filter press. Although, electric field was interrupted periodically, the temperature in the filter press rose from 20 to 65–90°C. Citeau et al. [9, 10] proposed to alternate initial constant electric current treatment (C.C.) by constant voltage treatment (C.V.) at late stages of electrodeewatering, in order to provide a better control of the heating. Also, the temperature may be controlled by the choice of a lower electric field and/or a shorter treatment time [9, 10, 22]. More generally, in order to avoid an excessive heating, a compromise is made between the selected electric treatment time, the intensity of electric field and the extent of dewatering. This limits the real performance of the technology.

1.3. Energy Consumption

It should be noted that the heating and the temperature profiles in the filter cake are not uniform: heating at anode side is significantly higher than at cathode side (general case of negatively charged sludge particles) [2, 8, 22]. It is explained by a higher dryness, the electrical resistance of filter cake and the lower filtrate flux at anode side of the filtration cell [2, 10]. Significant ohmic heating, high cake dryness and low filtrate flux at anode side can result in local desiccations of filter cake and filtering media surface, worsening the electrical contact between filter cake and anode. As a consequence, the electrical resistance and the current density rise, increasing energy consumption [9, 10]. This compels to terminate dewatering process before the maximal dryness is reached, and reduces the process efficiency.

Another reason of elevated energy consumption is high electrical resistance of filter cloth located between filter cake and anode [9, 21, 29]. Saveyn et al. [21] proposed to place anode in direct contact with the sludge and thus reduce the energy losses. However, this solution creates technological problems with the filter cake discharge after dewatering. Citeau et al. [9] showed that the energy consumption can be reduced on 70 % by using non-conventional filter cloth.

1.4. Acid And Alkaline Contamination Of Filtrate And Electrode Corrosion

Electrodewatering experiments are usually performed using “non-consumable” anodes from mixed metal oxide coated titanium meshes [9, 10, 21, 26, 30] or entire graphite plates [23]. The primary electrochemical process occurring at electrodes made from “non-consumable” materials is water electrolysis:

Continuous release of hydronium and hydroxide ions results in acidification and alkalization of filtrate respectively at the anode and at the cathode sides, and thus in chemical contamination of filtrate [2]. Ions H^+ and OH^- also migrate to the filter cake [10] that can affect the electrodewatering efficiency in the case of pH-sensitive sludges [31].

Uncontrolled appearance of zones with high electric current density (due the aforementioned cake surface desiccation and loss of electrical contact between the filter cake and the electrode) in combination of high temperature and low pH can shorten the

anode lifetime. At critical values of temperature and current density even mixed metal oxide coated titanium anodes can degrade because of the cracking and dissolution of active coating, or the oxidation titanium substrate oxidation [32]. This factor also complicates the commercialization of electrodeewatering.

1.5. Electrodes Flushing

Larue et al. [18] and Hofmann et al. [20] have modified the electrodeewatering equipment by introducing the electrodes flushing. Their experiments were realized at pilot [20, 33] and laboratory [18] filter presses. Usually, in electro-filter-presses the electrodes are placed in direct contact with the filter cloth. While in Hoffman's and Larue's installations the electrodes were spaced from the filter cloth, and the compartment between the filter cloth and the electrode was flushed by recirculating salt or buffer solution. Thus, the flushing solution rinsed out and neutralized the electrolysis products, preventing their migration in the filter cake [20, 33]. This is an important result, since it was shown previously that increasing of electrical conductivity of the filter cake can increase the electrical energy consumption during the electro-dewatering [34]. Moreover, flushing solution dissipated the generated ohmic heat out of the filter chamber [18].

Lee and Yang [35] in their study of soil electroremediation (without dewatering) proposed an idea to continuously redirect catholyte to anode and anolyte to cathode chambers of the electroremediation system. It was demonstrated that cross recirculation of catholyte and anolyte resulted in mutual neutralization and prevented electromigration of electrolysis products in the purified solid [35].

The pressure electrodeewatering technology with anode and cathode washing was tested for the concentration of pH-sensitive biopolymers and bentonite [18, 20]. However, these studies did not discuss the effect of the flushing on the filtrate quality, electric energy consumption, dewatering rate and dewatering limit. Furthermore, the installation proposed in these studies requires the use of a highly conductive flushing liquid that must be purified after the experiments.

The current paper proposes a new improvement in the sludge electrodeewatering: electro-filter-press with recirculation of filtrate at the anode side only. This improvement does not require significant modification of the standard filter press equipment. The idea is to control the pH, temperature and cake dryness at the anode side, where the physicochemical conditions are most aggressive. The filtrate recirculation (flushing of anode with filtrate recovered in the same experiment at both sides of the filter press) does not require the any using special flushing liquid or extra chemicals.

The aim of this work was to study the impact of anode flushing on the filtrate quality, electric energy consumption, dewatering rate and dewatering limit during the sludge electrodeewatering.

2. MATERIALS AND METHODS

2.1. Sludge

The drilling sludge (provided by Soletanche Bachy, France) was fluid bentonite aqueous suspension with the initial dryness of 17.9 ± 0.3 wt.%. The solid density was equal to

2220 kg/m³. The electric conductivity and pH of the sludge were equal to 1.9 ± 0.1 mS/cm and 8.3 ± 0.3 , respectively. The average particle diameter, measured by a laser diffraction size analyzer Mastersizer (Malvern Instruments), was equal to 6.7 ± 0.5 μm (with 10 % inferior to 0.6 μm and 90% inferior to 23.2 μm). The value of particle zeta potential in the initial suspension, measured by the method of electroosmotic transfer [2], was equal to -16 mV.

Preliminary dead-end filtration-consolidation tests were done in order to characterize the sludge filterability and the filter cake compressibility. These tests were performed in small one-sided vertical cylindrical plastic cell (cross sectional area 3.1 cm²), equipped with a piston for cake consolidation. The filtration curves (dependence of filtrate volume, V , on time, t) were analyzed by conventional methods of Ruth (in coordinates t/V vs. V) and Wakeman–Tarleton (in coordinates $\ln(dV/dt^{1/2})$ vs. $\ln t$) [36], and the values of specific cake resistance, α_{av} , average filter cake dryness, C_c , and ultimate cake dryness, C_∞ , were determined as it is described in [2]. The following values were determined for the constant pressure of 5 bars: $\alpha_{av} = (9.7 \pm 0.1) \cdot 10^{14}$ m/kg, $C_c = 66 \pm 1$ wt.%, and $C_\infty = 78 \pm 1$ wt.%.

2.2. Electrodeewatering Equipment And Protocol

The setup used for the sludge dewatering (filtration and electrofiltration) is presented in Fig. 1a. It consisted of a feeding tank connected to the pressurized air system and a modified laboratory dead-end filter press (Choquenot, France), DC power supply E861 (0–1 A, 0–600 V, Consort, Belgium), multimeter Fluke 45 (USA), electronic balance

PM6100 (Mettler, USA) for filtrate, and computer for data logging. The experiments were carried out at two modes: without anode flushing (Fig. 1b) and with anode flushing (Fig. 1c). A peristaltic pump and a cooling system were added to the setup in experiments with anode flushing for filtrate recirculation. The filtrate was cooled in a heat exchanger (water jacketed stainless steel spiral tube). The temperature of cooled filtrate was approximately equal to 20 °C.

The filtration cell was made of polypropylene; it consisted of a cylindrical central chamber (cross sectional area 24.6 cm², volume 69.5 cm³) with a central sludge inlet, and two side chambers with the grooves for filtrate drainage. Each side of the cell was covered by nylon filter cloth Nitex 05-1001-SK05 (Sefar-Fyltis, France), and filtrate was recovered at both sides of the cell. The grid-like electrodes were placed in direct contact with the filter cloth. The anode was made of titanium coated with mixed precious metal oxide layer (DSA from De Nora, Italy, provided by ECS – Electro Chemical Services, France); the cathode was made of stainless steel. The inter-electrode distance was constant and equal to 2.8 cm. Two plastic-coated K-type thermocouples were placed inside the filtration cell at cathode and anode sides.

2.3. Methodology Of Pressure Dewatering Or Electrodewatering Experiments

Initially, the feeding tank was filled with 0.6 L of raw drilling sludge. A constant pressure of 5 bars was used in all experiments. It pushed the sludge from the tank to the filter cell continuously during the dewatering.

The electrodeewatering experiments were performed at two modes. In the mode with anode flushing, 70 g of filtrate (obtained in the preliminary simple filtration tests) were initially used in order to fill the anode side chamber and tubes of the recirculation system. Then, the filtrates recovered from the anode and cathode sides of the cell during the electrodeewatering were cooled, mixed and continuously pumped through the anode compartment by the peristaltic pump (Fig. 1c). Thus, anode was flushed continuously with filtrate during the experiments. The pumping rate was equal to 1 mL/s.

In all electrodeewatering experiments the electric field was applied after 3 min of the beginning of filtration (pressure application). This time (determined in preliminary tests) was used for gradual increasing of the applied pressure to its maximal value in order to avoid the filter cloth and damage by hydraulic shock. Experiments were carried out with the application of direct electric current with a constant current strengths of 0.15 A and 0.20 A (i.e., 60 and 80 A/m², respectively) or a constant voltage of 28 V (i.e., 10 V/cm). The experiments continued until the filtrate flow rate decreased drastically. Simple filtration experiments without electric field application were performed during 6 h for the sake of comparison.

2.4. Data Analysis

The filtrate weight, voltage, electric current strength, and filter cake temperature at anode and cathode sides were recorded continuously during the dewatering. The values of pH and electric conductivity of mixed filtrate samples were measured in course of

experiments with the help of a multi-parameter analyzer Consort C532 (Fischer Scientific).

At the end of experiments, the final cake was accurately discharged from the cell and sliced in radial direction. The dry solid content in the slices was measured by drying at 105°C for 24 h.

The average dryness of the sample in filtration cell during dewatering, C_{av} , was calculated as

$$C_{av} = 1 + \rho_l / \rho_s \varphi - \rho_l / \rho_s \quad (3)$$

where ρ_l and ρ_s are the densities of liquid and solid, respectively, and φ is the average volume fraction of solid in the filtration cell determined as

$$\varphi = \varphi_0 \left(1 + V / V_{cell} \right) \quad (4)$$

where φ_0 is the volume fraction of solids in the initial sludge, V is the cumulative volume of filtrate and V_{cell} is the inner volume of filtration cell.

The supplied electric energy, P , was calculated as

$$P = \sum_{j=1}^n U_j I_j \Delta t \quad (5)$$

where Δt is the time interval between two recorded measures, n is the number of recorded measures, U_j and I_j are the voltage and electric current intensity at the j^{th} measurement, respectively.

The specific energy consumption, W , was expressed as energy per additional mass of filtrate (in kWh/kg of supplementary eliminated water):

$$W = dP / dV \quad (6)$$

All the experiments were done three times in order to confirm the tendencies. The curves shown in graphs represent the average values and the error bars represent standard deviations.

3. RESULTS AND DISCUSSION

3.1. Filter Cake Temperature, Dewatering Kinetics And Filter Cake Structure

Fig. 2 compares the variation of the filter cake temperature at anode and cathode sides during the electrodeewatering experiments with and without anode flushing (filtrate recirculation).

In all experiments, the initial temperature of the sludge was equal to 23°C. In conventional electrodeewatering experiments (without anode flushing, filled symbols) the application of electric field resulted in a significant increase of the temperature both at anode and cathode sides of the cell. In accordance with Joule's law, the filter cake heating and the temperature increase were more pronounced at higher electric current density:

$$Q \sim i^2 R \quad (7)$$

where Q is Joule heat, i is the current density, and R is the electrical resistance of cake layer. In experiments without anode flushing the temperature was notably higher at anode than at cathode (similar temperature gradient was observed by Loginov et al. [2]). This

can be explained by higher electrical resistance of thicker and denser filter cake layer and worse heat evacuation with filtrate at anode side. In experiments without anode flushing at current density ($i = 80 \text{ A/m}^2$), the temperature of anode exceeded 70°C . The temperature increase became crucial at late stage of the experiment (abrupt increase of error bars at 10000 s in Fig. 2a). This obliged to stop the experiments prematurely and did not let to use a higher current density for dewatering. In practice, this is one of the reasons limiting the industrialization of electrodeewatering technology.

The flushing of anode allowed controlling the temperature both at anode and cathode sides of the cell (Fig. 2). The temperature increase did not exceed 10°C near the anode and it was kept constant near the cathode even at higher current density. The ohmic heating existed regardless of the flushing, but in experiments with filtrate recirculation the filtrate recovered from cathode side was directed to the anode for the more efficient heat evacuation (Fig. 1c). This reduced the temperature at both sides of the filter press (Fig. 2) and allowed, in principle, further increasing of electric current density without the risk of equipment damage during electrodeewatering.

Fig. 3 presents electrodeewatering curves obtained in experiments with and without anode flushing.

The sludge dewatering without electric field application increased the average solid content from 18 wt.% to only 28 wt.% during 6 h. It may be concluded that the simple dewatering was inefficient because of the extremely high specific cake resistance, $\alpha_{av} =$

$9.7 \cdot 10^{14}$ m/kg. The application of electric field significantly reduced the dewatering time: the filter cakes with a final average dryness 69–72 wt.% were obtained in less than 5 h. The final dryness was not significantly influenced by the flushing stream or electric current strength.

As it was observed in the electrodeewatering experiments without anode flushing, about 98–99% of the total amount of filtrate was obtained from the cathode side. This may be explained by an extremely high resistance of the cake layer formed at anode side of the cell. Thus, the filtrate flux at cathode side was practically equal to the total filtrate flux, J , calculated as

$$J = S^{-1} dV / dt \quad (8)$$

where S is the cross sectional area of filter cell, V is the total filtrate volume, t is the time. Fig. 4 presents the dependency of J on V for different dewatering experiments.

In experiments without electric field application the filtrate flux decreased rapidly according to the cake filtration law $J \sim 1/(\alpha_{av} \cdot V)$ because of the cake formation at both sides of the filter press. The application of electric field significantly increased the dewatering rate and slowed down the flux decrease. According to Vorobiev and Jany [37], the electric field induced the electrophoretic flux of negatively charged sludge particles towards anode, and thus reduced the filter cake formation at cathode and promoted the solid accumulation at anode. The electrodeewatering may be divided in two stages: with slow flux decrease (roughly, $V < 290\text{--}300$ mL), and fast flux decrease ($V > 300$ mL) (Fig. 4). At the first stage ($V < 300$ mL) the electrophoretic flux counterbalanced

the convective flux of particles to cathode, and thus, filtrate was recovered from cathode side without significant flux decline [37]. At this stage, the flux was practically proportional to the electric field intensity: increasing of current density from 60 to 80 A/m² increased the filtrate flux on approx. 27% (Fig. 4), that is explained by increasing of electrophoretic flux on 30%, according to equation [37]

$$J \sim u_e \sim k_e E \quad (8)$$

where u_e is the electrophoretic rate of particles, k_e is the electrophoretic mobility, E is the local electric field strength in the cell. Slow decrease of the filtrate flux at this stage can be associated with decreasing of k_e during the sludge concentration, decreasing of W with the solid accumulation at anode, or by deposition of uncharged particles at cathode.

The first stage of electrodeewatering was completed when the filter press was filled by the filter cake, growing from anode side of the cell. The second stage of electrodeewatering was characterized by a significant flux decreasing, corresponding to the filter cake consolidation. Thus, major part of filtrate was recovered at the first more rapid stage of electrodeewatering. Regardless the dewatering conditions, the transition between two stages occurred, when 290–300 mL of filtrate were obtained (Fig. 4). According to Eqs.(3,4), this corresponded to the formation of a cake with average dryness $C_{av} = 66.2 \pm 0.6$ wt.%. This value is close to the filter cake dryness $C_c = 66$ wt.%, determined in preliminary filtration-consolidation tests. Table 1 presents the time, required for the filter cake formation at different electrodeewatering experiments, determined from Fig. 3.

At all studied conditions, the time required for the sludge dewatering was slightly longer in experiments with anode flushing as compared to simple electrodeewatering (+14 %, +20% and +32% at 60 A/m², 80 A/m² and 10 V/cm, respectively). This may be explained by higher viscosity of filtrate caused by lower temperature in the filter press in experiments with anode flushing (Fig. 1). Nevertheless, the anode flushing allowed to apply higher electric current strength without risk of filter cell overheating, and thus to reduce dewatering time.

Fig. 5 presents the dryness distribution in final cakes obtained after the cake consolidation stage of electrodeewatering experiments with and without anode flushing. Results for 60 A/m² are shown; the results for 80 A/m² and 10 V/cm agreed with those for 60 A/m² within the experimental error.

In both modes of electrodeewatering (with and without anode flushing), the dryness increased from cathode to anode sides of the cake. This can be explained by predominant cake formation at the anode side during filtration stage followed by cake consolidation in direction of the solid pressure gradient. Similar but less pronounced dryness gradients were reported by Saveyn et al. [38] for sewage sludge electrodeewatering.

The solid distribution profiles (Fig. 5) were practically identical along the filter cake, except the area in immediate proximity of anode, where dryness in experiments without anode flushing (~85 wt.%) was significantly higher as compared to experiments with

anode flushing (~75 wt.%). The latter is close to the value of the ultimate cake dryness, obtained in preliminary filtration-consolidation tests, $C_{\infty} = 77.6$ wt.%.

The anode side overdrying above this ultimate limit (in electrodeewatering experiments without anode flushing) can be explained by electroosmotic cake drainage and electrolytic gas formation [18]. Though these factors slightly increase the average cake dryness, the drying up of filter cake at anode side is strongly undesirable, since it worsens the electric contact between filter cake and anode, and thus increases ohmic heating (Eq. (7)) and energy consumption (Eq. (5)) [9, 10]. The anode flushing prevented the overdrying of anode part of the cake (Fig. 5), but did not reduce significantly the total average cake dryness, as it is shown in Figures 4 and 5.

3.2. Electric Field Strength/Current Strength And Specific Energy Consumption

Fig. 6 presents the dependence of the electric field strength and electric current density on the electrodeewatering time.

Under constant current density (Fig. 6a), the electric field strength rapidly increased at late stages of electrodeewatering in experiments without anode flushing. Similar rapid increase of electric field strength during the sludge electrodeewatering at constant current was reported for different sludges by Citeau et al. [9] and Yoshida et al. [39]. This increase can be explained by sudden rise of electrical resistance of the filter cake, caused by desiccation of anode side of the cake, and worsening of electrical contact between anode and filter cake (Figs. 5) at late stages of electrodeewatering. The worsening of

electrical contact causes local increase of current density that increases the risk of electrode and filter damage. These phenomena obliged prematurely terminate the electrodeewatering [10].

The anode flushing prevents anode desiccation (Fig. 5), thus the electric field strength remains near constant during the electrodeewatering experiments (Fig. 6, open symbols). This extends the period, when electrodeewatering can be continued without the risk of equipment damage. Under constant electric voltage (Fig. 6b), the desiccation of anode surface of the cake without anode flushing resulted in steep decreasing of the current density, while in experiments with anode flushing the current density remained near constant during the process (Fig. 6b).

It should be noted, that at earlier stage of electrodeewatering, the anode flushing slightly increased the electric field strength (Fig. 6a) and reduced the electric current density (Fig. 6b) in comparison to experiments without flushing. This could be explained by decreasing of the ionic conductivity of sludge, filtrate and filter cake with temperature decrease in experiments with anode flushing (Fig. 2).

Fig. 7 presents the evolution of specific energy consumption, calculated according to Eq. (6), during electrodeewatering experiments.

At all studied conditions, the specific energy consumption curves slowly increased with the increasing of the cake solid content during the first stage of electrodeewatering up to

$C_{av} \sim 66.2$ wt.%. This can be explained by the slow decreasing of filtrate flux during the cake formation (Fig. 4). When the filter cake formation was completed and the average dry solid content exceeded $C_{av} = 66.2\%$, the energy consumption increased more rapidly. This is explained by a significant decreasing of dewatering rate (Fig. 4) and an increasing of electrical resistance of the system (Fig. 6). In experiments without anode flushing, it is advisable to stop electrodeewatering just after the stage of cake formation, in order to avoid the anode overheating (Fig. 2) and drastic desiccation at anode side (Fig. 5) and, thus, to avoid the risk of equipment damage and the reducing of total energy consumption. Table 2 compares the values of specific energy consumption in experiments with and without anode flushing at the end of cake formation stage of electrodeewatering.

The specific energy consumption increased with increasing of applied electric current strength that can be explained by more significant energy dissipation due to the ohmic heating (Fig. 2). Also, it was observed that in experiments with anode flushing the specific energy consumption was higher as compared to simple electrodeewatering (+14 %, +24% and +20% for 60 A/m², 80 A/m² and 10 V/cm, respectively). This relative increase of the energy consumption is correlated with the relative increasing of electrodeewatering time in experiments with anode flushing (Tab.1). This suggests applying the anode flushing at later stages of electrodeewatering, when the risk of the equipment damage related with the temperature rise at anode side extinguishes the beneficial effect of temperature on filtration duration. Nevertheless, the specific energy consumption required for the electrically assisted dewatering of the drilling sludge ($E \sim$

0.04...0.05 kWh/kg, as shown in Table 2) was significantly lower as compared to the energy required for thermal sludge drying ($E \sim 0.6\text{--}1.2$ kWh/kg, as given by Mahmoud et al. [8]) arguing in favor of electrodeewatering technology.

3.3. Influence Of The Anode Flushing On Filtrate Quality

Fig. 8 presents dependence of filtrate pH on dewatering time in experiments with and without anode flushing.

The electric current application during dewatering experiments inevitably resulted in formation of H^+ and OH^- ions at anode and cathode sides of the cell, respectively, due to the water electrolysis (Eqs. (1,2)). As soon as filtrate was mainly obtained from cathode side of the cell (98–99% of total filtrate volume), the electrochemical reaction occurring at cathode (Eq. 1) had the most important impact on the total filtrate quality in experiments without filtrate recirculation (Fig. 8, filled symbols). Without filtrate recirculation the ions OH^- , generated at cathode, passed into filtrate and caused significant alkaline contamination of filtrate: the pH of filtrate quickly increased up to $\text{pH} = 11.9\text{--}12.0$. The H^+ ions, generated at anode, migrated to the filter cake in direction of cathode. Usually, filtrate and filter cake contamination downgrades the attractiveness of electrodeewatering technology.

In experiments with anode flushing, when the alkaline filtrate obtained at cathode was redirected into anode compartment of the cell (Fig. 2b), the pH increased only from $\text{pH} = 8.2$ to $\text{pH} = 9.8$. This can be explained by mutual neutralization (recombination) of the

electrolysis products. The value of pH = 9.8 remained constant during the filtration stage of electrodeewatering and gradually decreased to pH = 7–8.5 with the decrease of the filtrate flux obtained at the cathode side during the cake consolidation stage. Thereby, the anode flushing prevented the alkaline contamination of filtrate during the pressure electrodeewatering.

4. CONCLUSIONS

The efficiency of the anode flushing was evaluated at lab scale on the drilling sludge electrodeewatering. The application of an electric field of about 10 V/cm, simultaneously with filtration process allowed accelerating the filtrate flow rate from 9 to 17 times in comparison to conventional filtration. The sludge was concentrated from 17.9 wt. % to 66.2 wt. % of solids with a specific electric energy consumption of 0.04–0.05 kWh/kg of removed water. In experiments without anode flushing, shorter electrodeewatering time was attained in experiments at higher electric current density. But it also caused strong increase of anode temperature, desiccation of the filter cake from anode side, rise of voltage and significant alkaline contamination of filtrate. The recirculation of filtrate in the anode compartment of the filter cell allowed controlling the electric field strength and the temperature. Thus, the dewatering of the sludge has been extended at high electric field without damaging the filter equipment by drastic heating and without significant decrease of the electrodeewatering efficiency. Furthermore, it reduced the filtrate contamination by neutralization of the electrolysis products.

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Table 1. The electrodeewatering time (in minutes), required to reach the average cake dryness 66.2 wt. %

	60 A/m ²	80 A/m ²	10 V/cm
Without flushing	228 ± 17	156 ± 14	139 ± 10
With flushing	260 ± 14	187 ± 27	184 ± 7

Table 2. The specific energy consumption (in kWh per kg of filtrate) at the average cake dryness 66.2 wt. %

	60 A/m ²	80 A/m ²	10 V/cm
Without flushing	0.036 ± 0.002	0.042 ± 0.004	0.041 ± 0.004
With flushing	0.041 ± 0.003	0.052 ± 0.006	0.049 ± 0.002

Figure 1. The experimental setup (a) and presentation of experiments without (b) and with (c) anode flushing by filtrate.

Figure 2. Filter cake temperature at anode (a) and cathode (b) sides of the cake during the electrodeewatering without (filled symbols) and with (open symbols) anode flushing.

Experiments with constant current (60 and 80 A/m²) and constant voltage (10 V/cm).

Figure 3. Evolution of the average dry solid content in the cell, C_{av} , during electrodeewatering with (open symbols) and without (filled symbols) anode flushing. Experiments with constant current (60 and 80 A/m²) and constant voltage (10 V/cm). Dashed line corresponds to dewatering without electric field application.

Figure 4. Dependence of filtrate flux on filtrate volume in experiments with (open symbols) and without (filled symbols) anode flushing. Experiments with constant current (60 and 80 A/m²) and constant voltage (10 V/cm). Dashed line corresponds to dewatering without electric field application.

Figure 5. Dependence of local dryness in the final cake on the weight-normalized distance from anode to cathode sides (0 = anode, 1 = cathode). Electrodewatering at 60 A/m² with (open symbols) and without (filled symbols) anode flushing. Each set of points presents summarized results of 3 different experiments. Lines are drawn for the guidance of eye.

Figure 6. Evolution of electric field strength at constant current density (60 and 80 A/m²) (a) and evolution of electric current density at constant field strength (10 V/cm) (b) in experiments with anode flushing (open symbols) and without anode flushing (filled symbols).

Figure 7. Dependence of specific energy consumption on the dry solids content during the sludge electrodeewatering with anode flushing (open symbols) and without anode flushing (filled symbols).

Figure 8. Dependence of mixed filtrate pH on electrodeewatering time in experiments with (open symbols) and without (filled symbols) anode flushing.