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## EFFECTS OF COMBINED Fe-Al ELECTRODES AND GROUNDWATER TEMPERATURE ON ARSENIC REMOVAL BY ELECTROCOAGULATION

The removal of arsenic from groundwater by continuous electrocoagulation (EC) using combined Fe-Al electrodes at its natural temperature ( $16.1 \pm 0.2$  °C) was comprehensively evaluated. The results obtained indicated that all studied Fe-Al electrode combinations were able to reduce As concentration below  $10 \mu\text{g}/\text{dm}^3$ . Nevertheless, the Fe-Fe-Al-Fe electrode combination was the most suitable due to its highest arsenic removal capacity ( $0.354 \mu\text{g As}/\text{C}$ ) for the lowest charge loading  $68.4 \text{ C}/\text{dm}^3$ . The specific consumption of Fe was  $0.0339 \text{ kg Fe}/\text{m}^3$  and of Al electrodes  $0.0145 \text{ kg Al}/\text{m}^3$ . The operating cost was estimated at  $0.182 \text{ €}/\text{m}^3$ . The increase of the groundwater temperature by  $8$  °C from its natural temperature influenced increase of the Fe and Al electrodes dissolution rate by 30% and 17%, respectively and that of As removal efficiency by 16%. The residual Fe and Al concentrations in  $500 \text{ dm}^3$  of treated groundwater were below WHO guideline values for drinking water. Long-term field operation of the pilot-scale continuous EC reactor is required to validate effectiveness, reliability and robustness of the EC technique for arsenic removal from groundwater confirmed in laboratory conditions.

### 1. INTRODUCTION

The groundwater is the main source of water supply for about 1.9 million inhabitants in the Province of Vojvodina, a northern region of Serbia. Due to the absence of the adequate groundwater treatment facilities about 800 000 inhabitants consume drinking water that contains more than  $10 \mu\text{g}/\text{dm}^3$  of arsenic. In most cases, concentrations of arsenic in drinking water range from 50 to  $100 \mu\text{g}/\text{dm}^3$ , but there are municipalities where it ranges from 150 to  $250 \mu\text{g}/\text{dm}^3$  [1]. Arsenic is classified as a group I carcinogenic substance to humans and the WHO suggested  $10 \mu\text{g}/\text{dm}^3$  as the guideline value

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for its concentration in drinking water [2]. These facts confirm the importance of the urgent need for the development of groundwater community-scale As treatment technique that will be consistently effective for the treatment of the relevant regional groundwater physicochemical composition, reliable and robust in the field operation, cost-effective and operated with the minimal risk to safety and the environment.

The As removal techniques such as chemical coagulation, adsorption on activated aluminium oxide, reverse osmosis, oxidation/filtration ion exchange, adsorption require substantial treatment time, extensive footprint, skilled operators, several pH adjustments. The above-mentioned methods generate a considerable quantity of secondary pollutants and sludge [3, 4]. Consequently, the alternative techniques are needed, especially the community scale microutility type and to be powered by renewable energy. Such an alternative technique is electrocoagulation (EC) that utilizes the electrochemical process to produce chemical coagulants *in situ*. In electrochemical processes, dissimilar electrode materials and type of the combined electrode pairs are observed as important factors of the EC [5]. The most commonly used electrode materials are Al and Fe and they lead to high arsenic removal efficiencies of up to 99% [6]. However, the use of combined electrodes of different metals has not been studied in the treatment of real groundwater. A review of the studies on arsenic removal by EC with combined Fe-Al electrodes is summarised in Table 1.

Table 1

Arsenic removal conditions based on literature data, EC, synthetic solutions

$C_{As}$ [ $\mu\text{g}/\text{dm}^3$ ]	Mode	Electrode	$V$ [ $\text{dm}^3$ ]	Operational parameters	$R_{As}$ [%]	Ref.
$(2-30) \times 10^{-3}$	B	Fe-Al	0.1	pH 5–8, $U$ 3 V, treatment time 14 min, $T$ 20–30 °C	99.9	[7]
150	B	Fe-Al	0.65	pH 5–9, 1.75–7.5 A/m <sup>2</sup> , r.t.	99.3	[5]
150	C	Fe-Al -Al-Fe	1.57	pH 7.4, aeration intensity 0.05 dm <sup>3</sup> /min, 2.5 A/m <sup>2</sup> , r.t.	96	[8]
$1.32 \times 10^6$	B	Al-Fe	0.2	pH 5–8, $U$ 3 V, treatment time 15 min, $25 \pm 1$ °C	98.8	[9]
500	C	Al-Fe	4	0.47 A/dm <sup>2</sup> , pH 7.0, aeration intensity 0.32 dm <sup>3</sup> /min	99.94	[10]

$C_{As}$  – initial concentration of arsenic, B – batch treatment mode, C – continuous treatment mode,  $R_{As}$  – arsenic removal efficiency, r.t. – room temperature.

Gomes et al. [9] studied the effects of combined Fe-Al electrodes in batch mode on As removal from synthetic solution at 20–30 °C. Depending on the pH of the synthetic solution, As removal efficiency ranged from 78% to 98%. The authors found that adsorption onto iron and aluminium hydroxides/oxyhydroxides was the principal mechanism of As removal. Kobya et al. [5] investigated the effects of Fe and Al plate electrodes

and its method of connections to DC power supply on arsenic removal from synthetic solutions. The highest As removal of 99.3% was obtained for monopolar electrodes in serial connection with Fe electrodes at pH 6.5. Imran et al. [7] reported As removal from the synthetic solution obtained with combined Fe-Al electrodes in a 20–30 °C temperature range. As removal did not change importantly in the given temperature range (99.48–99.9%) however, it was found that the increase of temperature of the synthetic solution above 30 °C reduced the arsenic adsorption on Al/Fe hydroxides. Kobya et al. [8] investigated the arsenic removal efficiency from As a synthetic solution in an EC reactor in a continuous flow using eight combinations of Fe-Al electrodes. The highest As removal efficiency of 96% was obtained with Fe-Al-Al-Fe electrode combination.

Song et al. [10] employed the response surface method to investigate the optimization and mechanism of arsenic removal by EC using combined Fe-Al electrodes. The study confirmed that adsorption onto Fe and Al hydroxides/oxyhydroxides was the predominant mechanism of As removal. In conclusion, most of the researches were performed in the laboratory conditions, using synthetic solutions. Only two of five studies reported the application of continuous flow EC. The synthetic solutions had a temperature in the range of 20–30 °C (Table 1). The volumes of used EC reactors were in the range of 0.1–4 dm<sup>3</sup> and experimental runs lasted between 12 and 50 min, hence a limited volume of synthetic solution was treated per research. Further, the geometry of used EC reactors was very different, as well as the range of the key applied operational parameters (current density, cell voltage, flow rate, etc.), hence it is very complex to compare their performances. As removal efficiency was in the range of 86–99.3% (Table 1). Consequently, these results obtained with the treatment of synthetic solutions can differ from those obtained with the real groundwater at its natural temperature (higher than 20 °C) because a number of other organic and inorganic pollutants present in the real groundwater may interfere with arsenic removal processes and groundwater temperature affects various aspects of its treatment by electrocoagulation (EC). Hence, the novelty of this research is a comprehensive evaluation of the effects of combined Fe-Al electrodes on As removal efficiency from 500 dm<sup>3</sup> of real groundwater at its natural temperature (16.1±0.2 °C) in a laboratory-scale horizontal-flow continuous EC reactor, residual Fe and Al concentrations in the treated groundwater and EC reactor operational cost. Supplementary, the influence of the natural groundwater temperature on Fe and Al electrodes electrochemical dissolution rate and arsenic removal efficiency was also analysed.

## 2. EXPERIMENTAL

*Groundwater samples.* The raw groundwater was collected from one of production wells supplying the town of Temerin in the Republic of Serbia. Table 2 shows the main characteristics of the raw groundwater in the examination period. The raw groundwater was slightly alkaline, and a total arsenic concentration exceeded by ca. 3.5 times the WHO guideline value (WHO<sub>GV</sub>) for drinking water.

Table 2

Physicochemical parameters of the raw groundwater

Parameter	Value±sd
pH	8.3±0.39
Conductivity, $\mu\text{S}/\text{cm}$	782±15
TOC, $\text{mg C}/\text{dm}^3$	2.20±0.79
DOC, $\text{mg C}/\text{dm}^3$	2.09±0.69
COD Mn	6.1±2.2
$UV_{254}$ , $1/\text{cm}$	0.047±0.002
SUVA, $\text{dm}^3/(\text{m}\cdot\text{mg C})$	1.98±0.37
As, $\mu\text{g}/\text{dm}^3$	33.94±2.01
Mn, $\mu\text{g}/\text{dm}^3$	18.6±3.3
Fe, $\text{mg}/\text{dm}^3$	0.050±0.007
Temperature, $^{\circ}\text{C}$	16.1±0.2

TOC – total organic carbon, DOC – dissolved organic carbon, SUVA – specific ultraviolet absorbance,  $UV_{254}$  – UV absorbance at 254 nm, COD Mn – consumption of  $\text{mg KMnO}_4/\text{dm}^3$ .

*EC reactor.* A technical specification of the horizontal-flow continuous EC reactor with the treatment capacity of  $300 \text{ dm}^3/\text{day}$  (Fig. 1) and applied operational parameters are summarized in Table 3.

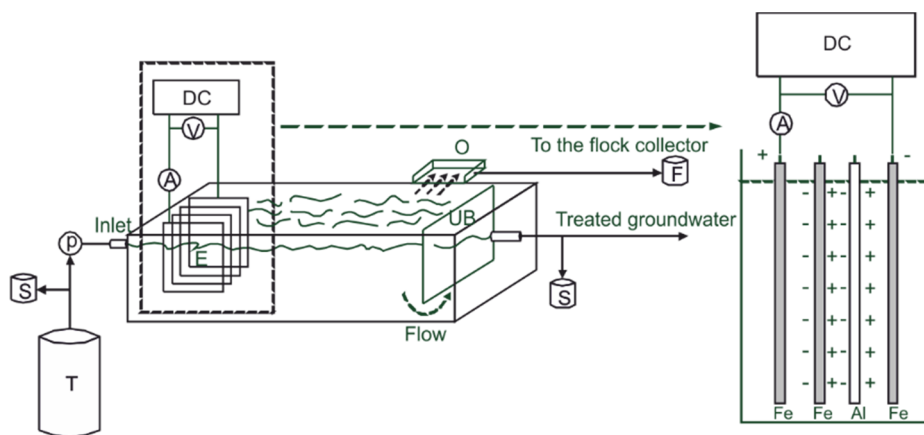


Fig. 1. EC reactor and electrical connection of Fe-Al electrodes: T – feed tank, P – centrifugal pump, E – combined Fe-Al plate electrodes, UB – underflow baffle, O – overflow for the evacuation of flocks, F – flock collector, A – amperemeter, V – voltmeter, S – sampling points

The combined plate Fe and Al electrodes were positioned normally to the flow of groundwater in the reactor. The hybrid Fe-A electrode pairs studied were: Fe-Fe-Al-Fe, Fe-Fe-Fe-Al, Fe-Al-Al-Fe and Al-Fe-Al-Fe. The outer electrodes were only connected

to the DC power supply (Fig. 1). There was no electrical connection between inner electrodes. Consequently, outer electrodes were monopolar and inner ones were bipolar. The voltage applied between the outer electrodes caused the polarization of the inner bipolar electrodes, which then present different polarities in the opposite faces. In line with conclusions of author's previous research, the polarity of combined Fe-Al electrodes (only outer electrodes) was changed at 30 min interval ( $t_{ch}$ ) in order to minimize passivation of EC reactor Fe-Al electrodes [12, 13].

Table 3

Technical specification and operational parameters of the EC reactor

Parameter	Value
EC reactor volume, $V$ , dm <sup>3</sup>	9
Electrode dimensions, $W \times L \times H$ , cm	14 × 13 × 0.3
Total effective electrode surface area, $S$ , m <sup>2</sup>	0.136
The distance between electrodes, $d$ , cm	1.2
Total volume of groundwater in EC reactor, $V$ , dm <sup>3</sup>	7.9
Ratio of electrode surface area over volume, $S/V$ , m <sup>2</sup> /m <sup>3</sup>	17.1
Groundwater flow rate, $Q$ , dm <sup>3</sup> /h	12
Reactor's hydraulic retention time, min	39
DC power supply source, model DF 1730 SB	0–30 V, 0–3 A
Centrifugal pump maximum power, W	30
Current density, $i$ , A/m <sup>2</sup>	1.98
Applied cell voltage, $U$ , V	10
Electrode polarity time change, min	30
Applied current, $I$ , A	0.36

*Experimental runs.* The groundwater pH was moderately adjusted from  $8.3 \pm 0.39$  to  $7.0 \pm 0.2$  by using hydrochloric acid to prevent pH exceedance above 8.5 in the reactor's stable state of operation. The groundwater with adjusted pH from the feed tank T (Fig. 1) was pumped into the EC reactor by a centrifugal pump. The geometry of the horizontal-flow continuous EC reactor enabled that coagulation, flocculation, settling and limited flotation occurred in parallel within the single volume. The time per one experimental run was 4 h for which about 50 dm<sup>3</sup> of groundwater was treated. The EC reactor was operated at conditions of optimal current density (1.98 A/m<sup>2</sup>) that generated low hydrogen bubbles density [13]. Flocks with As and other undesirable pollutants were only moderately evacuated from by electroflotation up to the surface of groundwater in the EC reactor. So generated scum was continuously removed through overflow O to the flock collector F. The EC reactor outlet zone begins with an underflow baffle UB that prevents floating sludge from escaping the reactor sedimentation zone. The groundwater was forced to follow a longer path due to underflow baffle than thereby created more time for settling.

*Sampling and analytical methods.* The treated groundwater samples were collected on 15 and 30 min intervals in the first 2 h and on 60 min intervals in the remaining 2 h

of experimental runs from the reactor's effluent flow S (Fig. 1). The samples were filtered on 45  $\mu\text{m}$  membrane filter. Effluent groundwater samples were analyzed for residual concentrations of As, Al, Fe. Further, pH, groundwater conductivity and temperature were measured for each taken sample. The analyses of As, Fe and Al concentrations in raw and treated groundwater were carried out by the atomic absorption spectroscopy (PerkinElmer Analyst 700) according to the standard method EPA 7010 (Graphite furnace atomic absorption spectrophotometry, Rev. 2, February 2007). pH measurements were carried out using a WTW InoLab portable instrument. Conductivity measurements were carried out with a Hanna model HI 933000. The groundwater samples were analyzed before and after EC treatment. Before and after each experimental run electrodes were weighed using a laboratory balance with the readability of 0.1 g. The groundwater temperature measurements were carried out with a laboratory thermometer with the readability of 0.1  $^{\circ}\text{C}$ . Experimental runs were carried out in duplicates and average values were used.

*Calculation methods.* The As removal efficiency  $R_{\text{As}}$  for the each of the employed Fe-Al electrode combinations was calculated using the following equation

$$R_{\text{As}} = \frac{C_0 - C_{t_{\text{EC}}}}{C_0} \times 100\% \quad (1)$$

where  $C_0$  is the concentration of As in raw groundwater and  $C_{t_{\text{EC}}}$  the residual As concentration after EC treatment.

Charge loading  $q_{\text{As, WHO}}$  ( $\text{C}/\text{dm}^3$ ) or charges transferred in electrochemical reactions for a volume of water treated is [16]:

$$q_{\text{As, WHO}} = \frac{It_{\text{EC, WHO}}}{v} \quad (2)$$

where  $I$  is the current applied (A),  $t_{\text{EC, WHO}}$  is the minimum EC time required to achieve the WHO guideline value in respect to residual As concentration (s) and  $v$  is the volume of groundwater in the EC reactor ( $\text{dm}^3$ ).

The average arsenic removed per Coulomb to reach  $\text{WHO}_{\text{GV}}$  for drinking water is As removal capacity ( $RC_{\text{As}}$ ) and was calculated for studied Fe-Al electrode combinations using the equation [5]:

$$RC_{\text{As}} = \frac{C_0 - C_{t_{\text{EC, WHO}}}}{q_{\text{As, WHO}}} \quad (3)$$

where  $RC_{As}$  ( $\mu\text{g}$  removed As/C) is arsenic removal capacity,  $C_0$  and  $C_{t_{EC, WHO}}$  are initial As concentration in the groundwater and its concentration in the groundwater ( $\mu\text{g}/\text{dm}^3$ )  $t_{EC, WHO}$ , respectively.

The EC reactor operating cost was calculated taking into consideration the main cost items excluding labour and maintenance cost:

$$OC = aC_{el, r} + bC_{Fe\ el, exp} + cC_{Al\ el, exp} + C_{As-ls} + aC_{el, pump} \quad (4)$$

where  $C_{el, exp}$  is the specific actual consumption of Fe and Al electrodes ( $\text{kg}/\text{m}^3$ ),  $C_{el, r}$  the specific electrical energy consumed by the EC reactor ( $\text{kWh}/\text{m}^3$  of treated groundwater) and  $C_{As-ls}$  is the cost of adequate transport, treatment and disposal of arsenic-laden sludge. The specific electrical energy consumed per  $\text{m}^3$  of treated groundwater was calculated using [18]:

$$C_{el, r} = \frac{UIt_{EC}}{v_{t_{EC}}} \quad (5)$$

where  $v_{t_{EC}}$  is the volume of groundwater treated for  $t_{EC}$  (h). The  $C_{el, pump}$  is electrical energy consumed by EC reactor pump per  $\text{m}^3$  of treated groundwater, which in average was  $2.08 \text{ kWh}/\text{m}^3$  for the flow rate of  $12 \text{ dm}^3/\text{h}$ . Further,  $a$  is the Serbian market electrical energy price ( $0.05 \text{ €/kWh}$  without VAT),  $b$  is the Fe electrode material price ( $0.057 \text{ €/kg}$ ),  $c$  is Al electrode material price ( $1.79 \text{ €/kg}$ ).

### 3. RESULTS AND DISCUSSION

#### 3.1. EFFECTS OF Fe-Al ELECTRODE COMBINATIONS ON As REMOVAL

The studied Fe-Al electrode combinations are listed in Table 4. The effects of the four different electrode combinations on As removal from groundwater were assessed and results have been presented in Fig. 2a. After approximately 60 min, the EC reactor achieved a stable state with respect to residual As. The pH values for all electrode combinations were relatively stabilized during the steady state being below pH for drinking water (Fig. 2b). For all the studied Fe-Al electrode combinations, concentrations of arsenic in drinking water were decreased below the  $WHO_{GV}$ . The swift As removal was observed at the beginning of the EC process when arsenic ions were abundant at the electrolysis start.

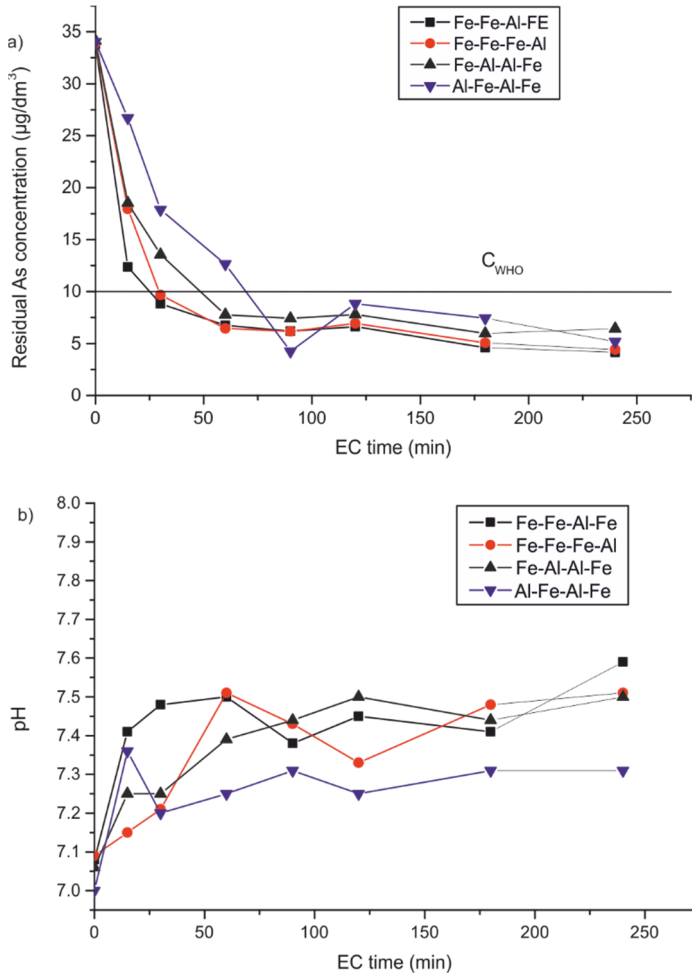


Fig. 2. Effects of Fe-Al electrode combinations on the time dependences of residual As in the treated groundwater (a), and groundwater pH (b);  $Q = 12 \text{ dm}^3/\text{h}$ ,  $i = 1.98 \text{ A}/\text{m}^2$

Further, Fe or Al hydroxides generated by the anodic electro dissolution form time dependent complexes dragged out by the feed-groundwater flow out from the reactor [15]. However, the most efficient As removal with respect to lower EC reactor operating time was obtained for the Fe-Fe-Al-Fe combination. It had the lowest operating time of approximately 25 min reaching the  $\text{WHO}_{\text{GV}}$  for As in drinking water. The average As removal efficiency with respect to raw groundwater in the EC reactor stable state (higher than 60 min) for the electrode combinations Fe-Fe-Al-Fe, Fe-Fe-Fe-Al, Fe-Al-Al-Fe, and Al-Fe-Al-Fe was 82%, 81%, 79%, 79.6%, respectively (Table 4).

The EC reactor should operate under minimum charge loading required to obtain treated groundwater complying with drinking water standards and to preserve the cost



effectiveness of the process [13]. The residual arsenic concentration as a function of  $q_{As, WHO}$  for the studied Fe-Al electrode combinations is shown in Fig. 3.

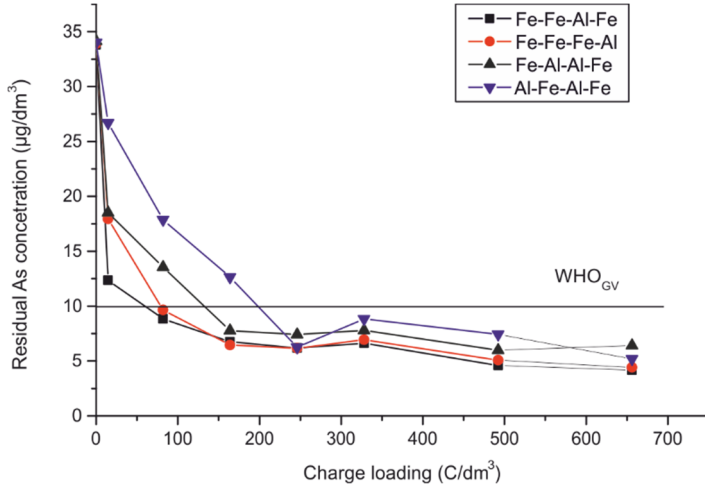


Fig. 3. Effects of charge loading on Al residual concentration for various electrode combinations;  $Q = 12 \text{ dm}^3/\text{h}$ ,  $i = 1.98 \text{ A/m}^2$ ,  $t = 16.1 \pm 0.2 \text{ }^\circ\text{C}$

As seen in Fig. 3, upon increasing charge loading the As removal increases, however differently for various Fe-Al electrode combinations. The residual As concentration for Fe-Fe-Al-Fe, Fe-Fe-Fe-Al, Fe-Al-Al-Fe, Al-Fe-Al-Fe electrodes reached the values below  $WHO_{GV}$  for drinking water within ca. 25, 31, 50, and 70 min, respectively (Fig. 2a). Hence, using Eq. (2), the required  $q_{As, WHO}$  values have been calculated to obtain the residual As concentration in treated groundwater below  $WHO_{GV}$  level for above listed combinations of Fe-Al electrodes (summarized in Table 3). The results are given in Table 4. The minimum charge loading of  $68.4 \text{ C/dm}^3$  required to reach the  $C_{As, WHO}$  guideline was obtained for Fe-Fe-Al-Fe electrode combination.

Table 4

. Effects of Fe-Al electrode combinations on As removal efficiency

Electrode combination	$R_{As}$ [%]	$C_{Al, el}$ [kg/m³]	$C_{Fe, el}$ [kg/m³]	$q_{As, WHO}$ [C/dm³]	$RC_{As}$ [µg As/C]	$OC$ [€/m³]
Fe-Fe-Al-Fe	82	0.0145	0.0339	68.4	0.354	0.182
Fe-Fe-Fe-Al	81	0.0178	0.0545	82.0	0.295	0.197
Fe-Al-Al-Fe	79	0.0287	0.0361	133.7	0.182	0.240
Al-Fe-Al-Fe	79.6	0.0107	0.0343	205.1	0.119	0.176

The EC reactor electrode specific consumption is presented in Fig. 4. It is based on the weight of each electrode separately before and after the respective experimental run.

The smallest specific total Fe and Al electrode consumption of  $0.045 \text{ kg/m}^3$  had Al-Fe-Al-Fe electrode combination, and the highest one was observed for Fe-Fe-Al-Fe combination with specific electrode consumption of  $0.0648 \text{ kg/m}^3$  (Table 4).

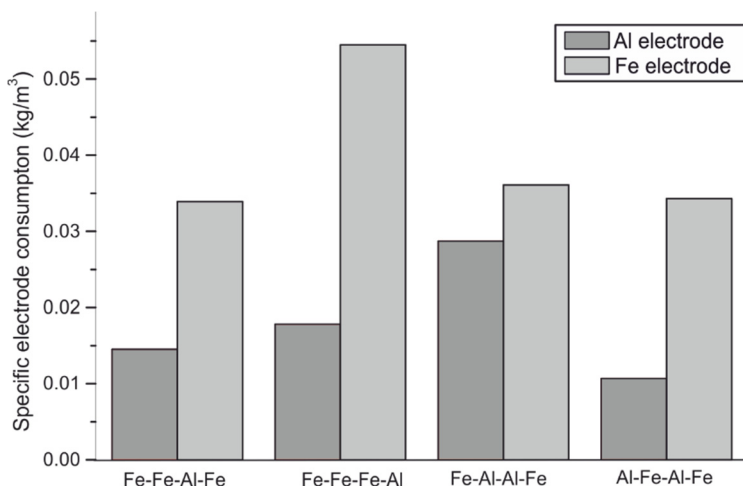


Fig. 4. Specific Fe-Al electrode consumption;  
 $Q = 12 \text{ dm}^3/\text{h}$ ,  $i = 1.98 \text{ A/m}^2$ ,  $t = 16.1 \pm 0.2 \text{ }^\circ\text{C}$

The average amount of arsenic removed per 1 C to reach the  $\text{WHO}_{\text{GV}}$  for drinking water or As removal capacity was also calculated using Eq. (3) (Table 4). It varied from  $0.119$  to  $0.354 \text{ } \mu\text{g As/C}$  and the maximum arsenic removal capacity was achieved for a Fe-Fe-Al-Fe electrode combination. In conclusion, for all studied Fe-Al electrode combinations As concentration decreased below  $10 \text{ } \mu\text{g/dm}^3$ . The fastest As removal with respect to lowest operating time and charge loading required in treated natural groundwater below  $10 \text{ } \mu\text{g/dm}^3$  was obtained for the Fe-Fe-Al-Fe electrode combination. The residual concentration of the electrode material in treated solutions by electrocoagulation is irregularly reported in the literature, however it is equally important parameter as the As removal efficiency. The effects of Fe-Al electrode combinations on residual Fe and Al concentrations in treated groundwater was assessed and the results presented in Fig. 5. The residual Fe and Al concentrations of treated groundwater for all studied Fe-Al electrode combinations were below the  $\text{WHO}_{\text{GV}}$  for drinking water. This result confirmed that for the applied operational parameters (Table 3) EC reactor with studied combined Fe-Al electrodes is capable of treat natural groundwater and meet international drinking water standards for Al and Fe.

The operational cost of EC reactor ( $OC$ ) includes mainly the cost of the Fe and Al electrodes consumption, the cost of EC reactor electrical energy consumption, sludge treatment and disposal cost, and the cost of maintenance and labour. The arsenic-laden

sludge management is a primary environmental concern of all arsenic remediation technologies. It was estimated that the cost of transportation and disposal of sludge in the hazardous landfill in India should present about 5% of EC reactor operational cost per unit of treated groundwater [19]. This assumption but doubled to 10 % was used in this calculation.

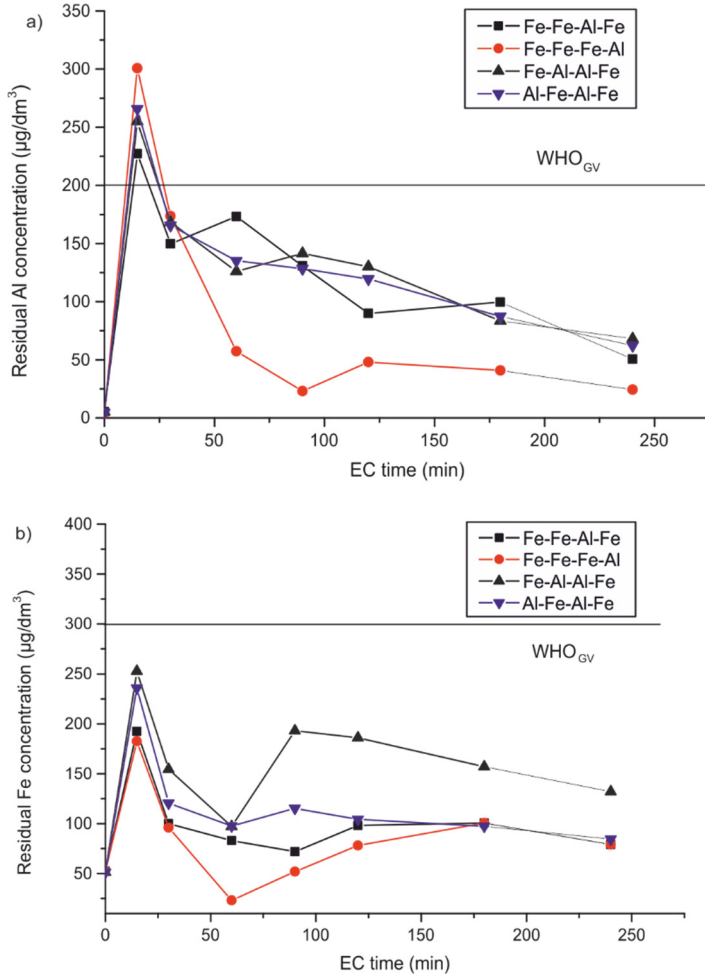


Fig. 5. Effect of Fe-Al electrode combinations on the residual Al and Fe concentration;  
 $Q = 12 \text{ dm}^3/\text{h}$ ,  $i = 1.98 \text{ A/m}^2$ ,  $T = 16.1 \pm 0.2 \text{ }^\circ\text{C}$

The operational cost for Fe-Al electrode combinations was calculated using Eq. (4) and the cost was in the range of 0.176 €/m<sup>3</sup> for Al-Fe-Al-Fe electrode to 0.240 €/m<sup>3</sup> for Fe-Al-Al-Fe. The obtained EC reactor operating cost was in the acceptable range comparing the current drinking water price in Serbia that is about 0.6 €/m<sup>3</sup>. The operating

cost range obtained in this research for Fe-Al electrode combinations was higher comparing with the results obtained in author's previous research when only Fe electrodes were used ( $OC$  was  $0.0135 \text{ €/m}^3$ ) for similar EC reactor operational parameters [13]. The main reason for the increase is the price of Al electrodes that is 96% higher than that of Fe electrodes and the cost of electrical energy consumed by EC reactor pump per  $1 \text{ m}^3$  of treated groundwater that was not previously taken in consideration.

### 3.2. EFFECTS OF NATURAL GROUNDWATER TEMPERATURE ON As REMOVAL

The effect of temperature on As removal efficiency has not been widely studied in literature and much of contradictory results reported so far can be influenced by the synthetic solution and/or groundwater temperature [18]. The obtained As removal efficiency from the natural groundwater at  $16.1 \pm 0.2 \text{ °C}$  for all studied Fe-Al electrode combinations (Table 4) in this research was lower comparing with robust literature results summarised in Table 1 that were in the range 86–99% for synthetic solutions at  $20\text{--}30 \text{ °C}$ . The residual As concentration was determined for natural groundwater temperature of  $16.1 \pm 0.2 \text{ °C}$  and  $24.6 \pm 0.5 \text{ °C}$  and similar EC operational parameters (current density, flow rate, initial pH and inner electrode polarity time change) and Al-Fe-Al-Fe electrode combination. The results obtained are presented in Fig. 6.

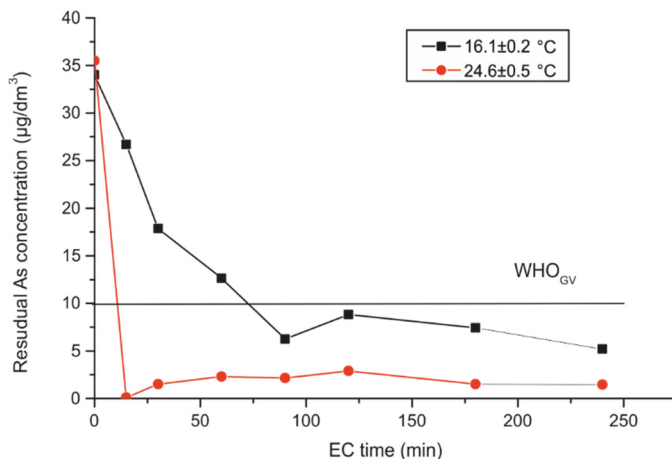


Fig. 6. Effects of groundwater temperature on residual As concentration with EC time;  $Q = 12 \text{ dm}^3/\text{h}$ ,  $i = 1.98 \text{ A/m}^2$

As seen in Fig. 6, groundwater temperature has significant effects on EC time required to reach the residual As concentration below  $10 \text{ µg/dm}^3$ . The As concentration in treated groundwater below  $WHO_{GV}$  was achieved after approximately 20 min of treatment at  $24.6 \pm 0.5 \text{ °C}$ , however, at natural groundwater temperature ( $16.1 \pm 0.2 \text{ °C}$ ) it was achieved after 70 min. The average As removal efficiency at  $16.1 \pm 0.2 \text{ °C}$  was 79.6% and 95% at

24.6±0.5 °C. The residual As concentration in the treated groundwater for EC reactor stable state of operation (higher than 60 min) at 16.1±0.2 °C and 24.6±0.5 °C was 6.92±2.2 µg/dm<sup>3</sup>, 1.96±0.94 µg/dm<sup>3</sup>, respectively. The minimum charge loading to reach the residual As concentration below WHO<sub>GV</sub> at 16.1±0.2 °C was 205.06 C/dm<sup>3</sup>, at 24.6±0.5 °C it was 27.34 C/dm<sup>3</sup>. The electrical conductivity of groundwater at 24.6±0.5 °C was 860 mS/cm, 707 mS/cm at 16.1±0.2 °C. At 16.1±0.2 °C the dissolution of Fe electrodes was lower by ca. 30% compared to that at 24.6±0.5 °C, while for Al electrodes it was lower by 17%.

In conclusion, natural groundwater temperature has a strong impact on Fe and Al electrode dissolution rates, EC treatment time required to reach the residual As concentration below WHO<sub>GV</sub> for drinking water and the level of the As removal efficiency. Therefore, the use of real groundwater at its natural temperature in a laboratory-scale study is a priority to obtain adequate operational parameters for EC reactor scale-up figures important for the design of the pilot-scale stage of research.

#### 4. CONCLUSION

The performance of the laboratory-scale continuous flow EC reactor with the combined Fe-Al electrodes was comprehensively assessed for removal of As from natural groundwater at its natural temperature of 16.1±0.2 °C. The EC reactor with combined Fe-Al electrodes in a continuous-flow mode seems to be a promising and affordable candidate tool for removal of As from groundwater for small rural settlements. The Fe-Fe-Al-Fe electrode combination gave highest As removal efficiency (82%) with respect to the lowest operating time (25 min) and charge loading (68.4 C/dm<sup>3</sup>) required to achieve residual As concentration in treated natural groundwater below 10 µg/dm<sup>3</sup>. Upon stable operation phase of the (higher than 60 min), the residual Fe and Al concentrations were below the WHO<sub>GV</sub> for drinking water. The operational cost was 0.182 €/m<sup>3</sup>.

Further studies should focus on a prolong (several months minimum) field pilot-scale phase research to finetune EC reactor operational parameters, to use onsite renewable energy sources and to assess in detail cost-effectiveness of the practical application of electrocoagulation for As removal from groundwater.

#### ACKNOWLEDGEMENT

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