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АВТОМАТИЗАЦІЯ ТЕХНОЛОГІЧНИХ ПРОЦЕСІВ

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MODELLING OF HIGH PERFORMANCE ELECTROCOALESCER BASED ON EXPERIMENTAL DATA

Modern approaches to automatic control of crude oil dewatering and desalting are predominantly model-free, and described model-based systems lack precise mathematical description. Not a single research provides a dynamic input-output model for electric dehydrator, suitable for control system development. As far as electric dehydrator, which is the main plant to control in the process, is a non-linear system with distributed parameters, a need for linearization arises. The aim of present study is to compare different methods for obtaining approximate transfer function of an electric dehydrator from graphical experimental data.

Key words: *mathematical modelling, identification, transfer function, first-order system with time delay, least squares approximation, integrated squared error criterium.*

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The problem statement. Crude oil naturally has many impurities, like sand, resin, water, chlorides and other salts etc. Amount of all these impurities is strictly constrained due to both possible harm those pollutants can do to industrial plants and quality demands to end products. Water removal from the crude oil is one of the most challenging stages of crude oil pretreatment, since water is contained in form of tiny (common diameter scale is 1 to 10 μm) drops of fluid distributed in oil, forming water-in-oil emulsion. Besides water naturally appearing in crude oil, more water incomes during extraction and then water is usually added into crude in order to dissolve salts. The mix is then agitated and emulsified so that water could eliminate the most possible amount of salt. For this reason, percentage of water in crude during pretreat might be quite high (up to 30 – 40 %).

The most efficient way of demulsification is electrostatic separation performed using special plants called electrocoalescers. Emulsion is continuously pumped through the vessel with electrodes mounted within. Powered by DC, pulsed DC or AC, they generate electric field that forces water drops to move toward each other and coalesce forming larger drops so that they could settle downwards more easily.

In order to make development of model based electrocoalescer control system possible, it is necessary to determine its transfer function. As an object for automatic control, electrocoalsescer is considered to be a non-linear, distributed parameter system. Such systems are especially difficult to model and control, compared to lumped parameter systems. In fact, we are far from complete understanding of all physical processes taking place during electrocoalescence, so that deriving a purely analytical model lacks fundamental results. In addition, methods and devices for non-linear control systems are far less widely developed than for linear systems. However, any distributed parameter system may be approximated with a lumped-parameter system, and non-linear system may be linearized in the neighborhood of a point of its static characteristic.

If one first determined a formula representing plant transfer function with unknown coefficients, unknown coefficients might then be calculated from experimental data such as step response, impulse response, frequency response etc.

Analysis of previous research. Several models describing physics of the process are known. Also, many simulations and experimental investigation were done in order to obtain empirical and correlation dependencies.

An extensive review work about state of the art in crude oi desalting and dewatering by electrocoalescence is presented in [1]. It includes both early and novel mathematical models of processes occurring during electrocoalescence, qualitative characteristics of common phenomena, prospective directions of further research and constructions of commercial, industrial electrocoalescence units. Most results regard distinct stages of water droplets coalescence in electric field, and none of reviewed research works develops a mathematical model for a real emulsion in an industrial plant, which could be used for obtaining a useful input-output model.

Specific studies are mainly focused on statics, i.e., desalting and dewatering quality without reference to transient-time dependencies. Article [2] is dedicated to obtaining statistical dependencies of demulsifying quality on different process conditions including field strength, initial water cut, emulsion temperature etc., using experimental data. Optimal temperature, demulsifying agent concentration, settling time, mixing time and washing water ratio were calculated using combination of demulsification and desalting quality as an optimization objective. In a similar manner, authors of [3] utilized an experimental setup with different crude oils to perform correlation-based analysis of influence of different parameters on desalting quality. Resin content and acidity number were claimed to be the most important properties of crude oil in context of demulsification. This is an important result, but such properties are usually a given input with no possibility of altering it much. In other words, they hardly might be the thing to be changed by control signal. Also, both results hardly can be extrapolated to a wide range of crudes and plants, and are difficult to obtain repeatedly for each industrial implementation.

In paper [4], a mathematical model of electrocoalescence, based on population balance method, was proposed and used for prediction of water droplets radii distribution after coalescence. Influence of temperature and current frequency was examined. Some static characteristics were given, but proposed models are suitable for physical description only, not for specific control system designing.

A comparison of two popular CFD approaches to electrocoalescer modelling – Eulerian and VOF models – is done in [5]. Plant data were used as sample for comparison. Their performance was changing with operation conditions, so that mathematical modelling should concern of choosing modelling approach depending on process peculiarities. Such pitfalls make modelling process more complicated, and that increase the need for more general approach.

A few articles consider dynamical processes and electrocoalescers performance. In work [6] transition coalescence process was investigated using a static volume of emulsion with immersed electrodes in different positions. Those results are hardly suitable for identification due to dramatic difference between experimental setup and a real coalescer with constantly flowing emulsion.

As far as theoretical derivation of transfer function is problematical, value of identification methods, like described in [7 – 8], raises significantly. Appropriate experiments are easier to set up and perform, so that one can obtain necessary data for wider range of industrial plants and crude oils.

Authors of paper [9] provided detailed results of dynamical electrocoalescence results in terms of number of droplets for several radius spans from tens to hundreds of micrometers. Experiments for the same sets of operation conditions were repeated many times, but without replacing emulsion, i.e., emulsion was treated again and again which resulted in different initial conditions of those experiments. This makes these results much less appropriate for transfer function calculation.

The best experimental data for approximate transfer function found is presented in [10], where step response was measured for a specific construction of electrocoalescer for different operation conditions. Although that article contains only graphically represented data, we consider it suitable for approximation needs.

Finally, for the sake of completeness, we leave a reference to a dissertation [11], which is the only work we've found, where transfer function of an electrocoalescence unit was used for calculations. Unfortunately, it regards concentrations of emulsion components and mass balance in the plant, not one of input-output channels which are actually used for process control.

Goal formulation. The purpose of the current article is to obtain transfer function of High Performance Electrostatic Coalescer (HPEC) as if it was linear time-invariant system. Prerequisites for this is a set of graphical data gathered with an experimental setup utilizing HPEC.

Presentation of the main material. The typical model of an industrial plant is n-th order system model without zeros, i.e., numerator contains only static gain and, maybe, time delay multiplier. Its transfer function is

$$W(s) = \frac{K' e^{-\tau s}}{\prod_{i=1}^{n}(s + s_i)} = \frac{K e^{-\tau s}}{\prod_{i=1}^{n}(T_i s + 1)} \tag{1}$$

where $(-s_i)$ stands for i-th root of the characteristic polynomial, i.e., i-th pole of the system; K' stands for static gain for representation via poles; T_i stands for i-th time constant, $K = (K / \prod_{i=1}^{n} s_i)$ stands for static gain for representation via time constants; τ stands for time delay of the plant.

The experimental setup, used in work [10], is a closed contour, consisting of shear valve, High Performance Electrostatic Coalescer (below, HPEC), heat exchanger, pump and some auxiliary elements. This contour emulates work of a bypass plant for crude oil demulsification. The experimental process was the following:

1. Water emulsion was pumped through the system for 10 minutes to stabilize water droplets size;
2. HPEC was enabled for predefined period of time (see below);
3. HPEC and pump were disabled to initiate water separation.

All plotted measurements were performed for this stage. Residual water cut is measured continuously with a capacity probe. Separation process was occurring in static emulsion, cause static mixer part of the HPEC made droplets sedimentation impossible. Detailed description of the construction of the HPEC is given in [12].

Consider figures 1 to 3 with transient time plots for HPEC with different operation conditions, taken from [10]. On the legend, C00 stands for a plant without static mixers, so that nothing contributes to increased turbulence of the flow; and C08 stands for a plant with them. The default experiment conditions, excluding the parameter that is varied in specific experiment, are: voltage between electrodes U = 6,0 kV, crude oil temperature t^o = 50 °C, initial water cut w_0 = 30 %, treatment time τ = 10 min.

C00 assembly is out of scope due to its low efficiency compared to C08, so that all the analysis is provided for the latter design.

Step responses (figures 1 to 3) distinctively show up that system is close to first-order one because of immediate change in derivative of the system output. The exceptions are:

- fig. 1: C08 with zero voltage (non-minimum phase, integrator-like behaviour with positive gain);
- fig 2: C08 with zero voltage (the same as described for fig. 1);
- fig. 3: C00 with zero voltage, C08 with zero voltage (the same as described for fig. 1), C08 with treatment time 2 min (non-minimum phase aperiodic-like behaviour with negative gain).

These plots are significantly different from those which might represent a first-order system, and no of first-order approximations will give a satisfying precision. Due to that, mentioned plots are not considered in calculations.

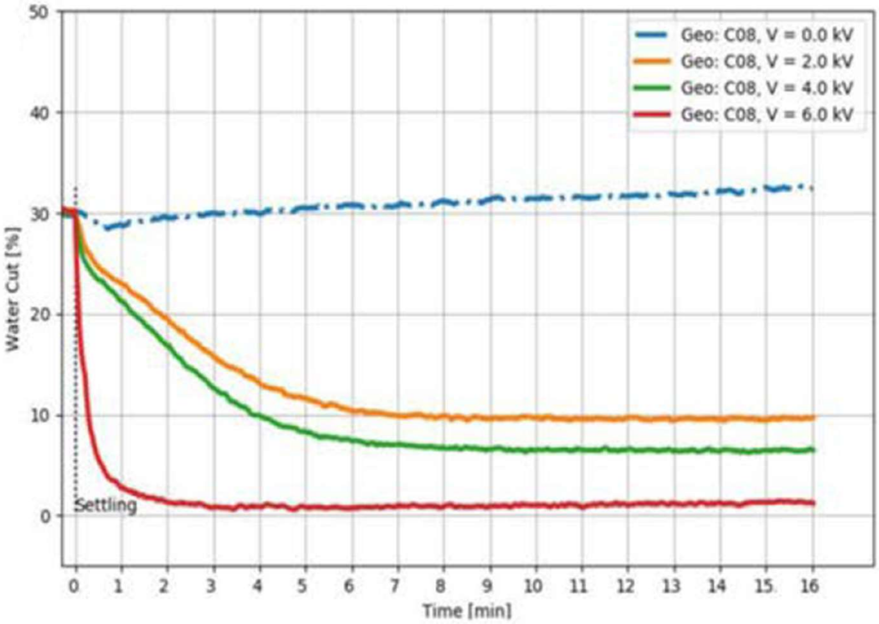


Fig. 1 – Step response of the system for different voltage between electrodes

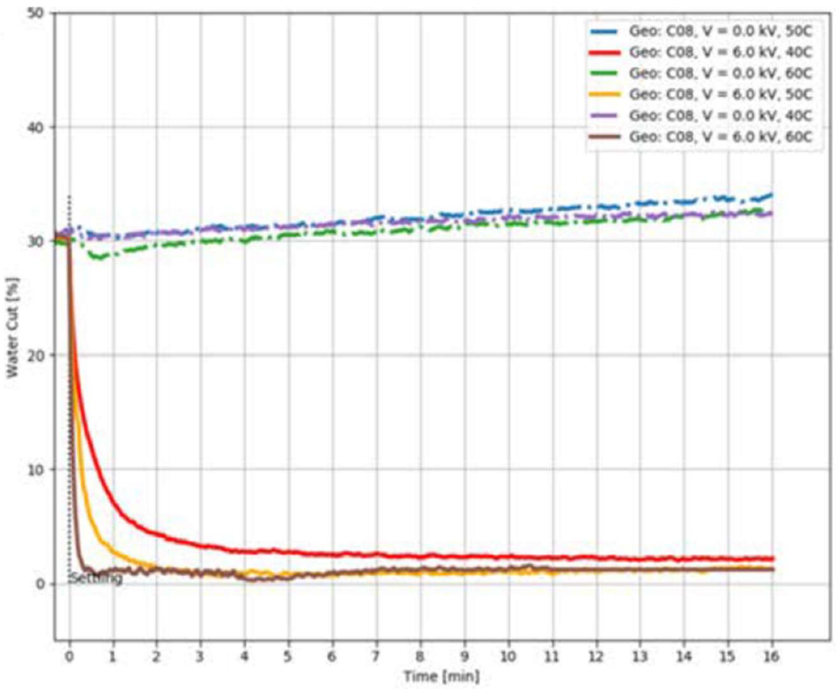


Fig. 2 – Step response of the system for different temperature of crude oil

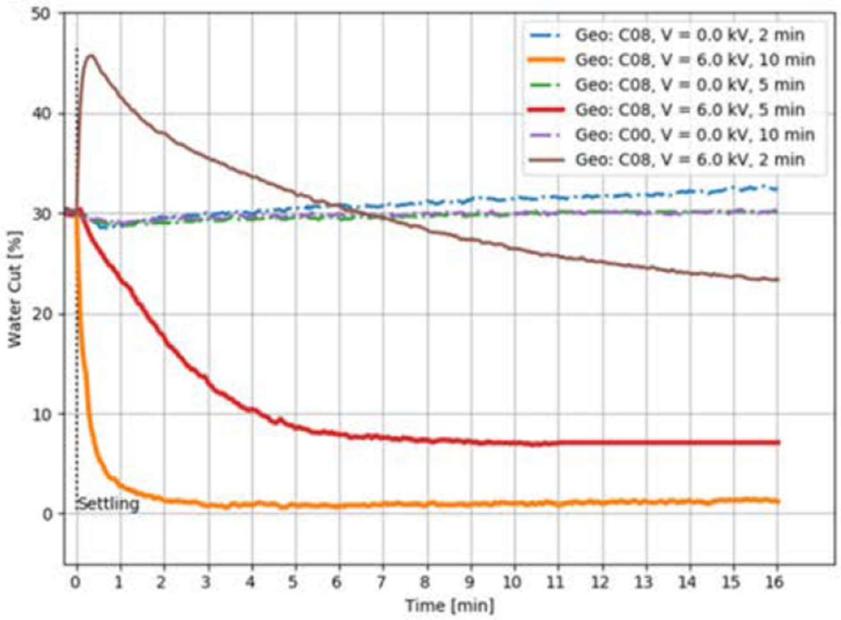


Fig. 3 – Step response of the system for different treatment time

Behavior of the system in all dynamic processes, except those were specially mentioned above, resembles behavior of a first-order system. Thus, approximate transfer function is

$$W_1(s) = \frac{Ke^{-\tau s}}{Ts+1} \tag{2}$$

It is worth mentioning that time delay arises because of separated electric treatment and sedimentation. Unknown numeric values of the model are static gain K, time constant T and time delay τ. Time delay is equal to the treatment time as far as water drops start settling only when treatment is finished. Details on fig. 4.

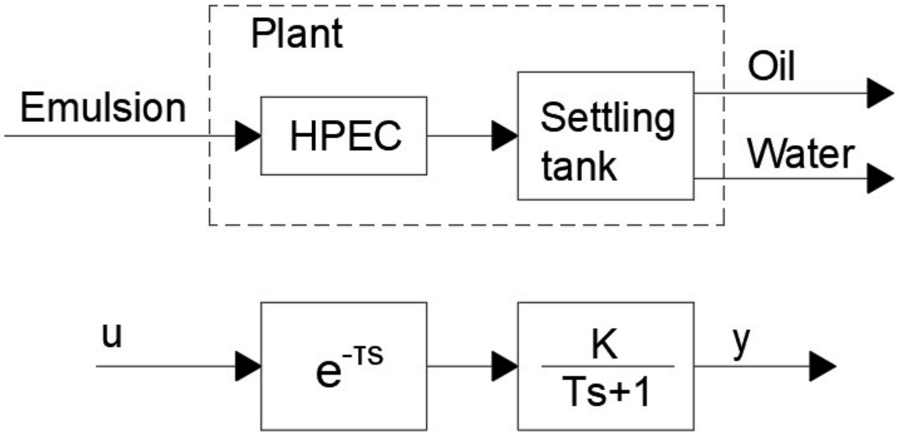


Fig. 4 – Principal plant (above) and open-loop control system structure

where u is manually set control signal, y is real water cut on the output of the system. Below, only the part with zero delay is identified since time delay is known.

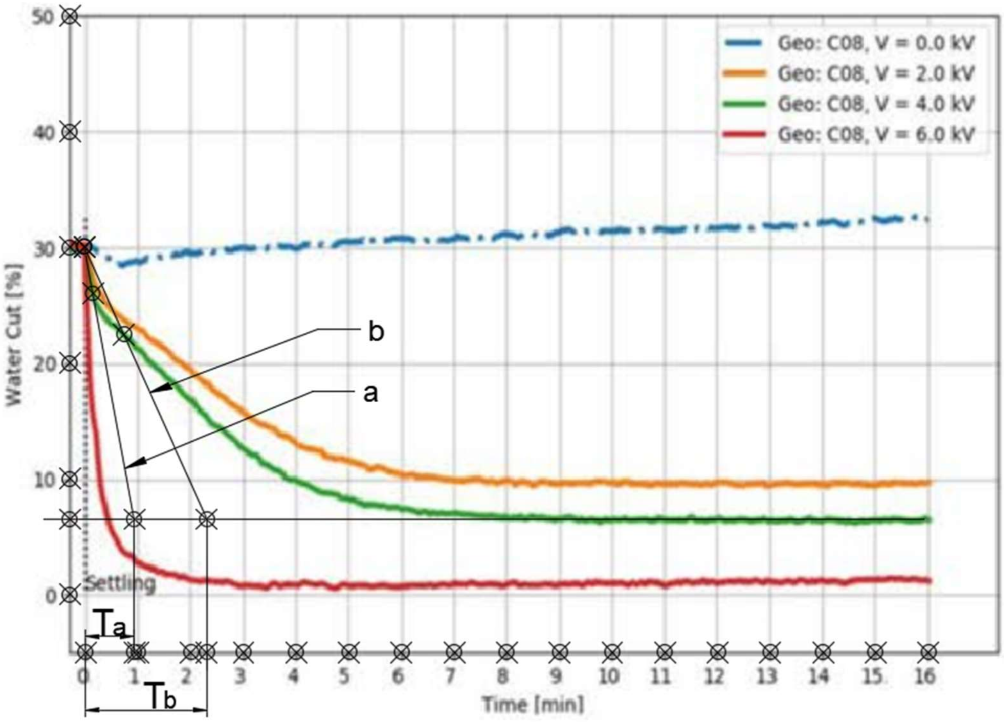
Static gain is calculated using the following formula:

$$K = \frac{y_s - y_0}{x_s - x_0} = \frac{y_s - 30}{x_s - x_0} \tag{3}$$

where y_s is static water cut on the system output (after settling in the tank), y_0 is water cut on the system input, x_s is value of varied parameter in the current experiment (below it is referenced as control signal), x_0 is the ambient, or default, value of that signal. For example, if control signal is emulsion temperature $t°$, then its value in experiments x_s may be 40 °C, 50 °C or 60 °C. Ambient temperature may be different due to environmental conditions. For example, this value might be 20 °C as if the crude oil and emulsion had temperature of the air around the plant in a mild climate. Initial water cut y_0 is always 30 % due to the experiment setup. In order to obtain numeric value for y_s, we draw a horizontal line, which is an asymptote of the water cut plot.

Then we draw a line, tangent to water cut plot from the initial point of the process upon intersection with the previously drawn asymptote. Abscissa of the intersection point is approximately equal to the time constant in the plant model. Both procedures are well-known and are a direct consequence of the general formula for step response of a first-order system. For processes for $U = 2\ kV$ and $U = 4\ kV$ there exists a time segment where water cut decreases more rapidly, and two ways of drawing an approximate tangent line are possible. They are shown on fig. 5. Line a is the real tangent line, while b is a secant line.

All drawing and measurement operations are performed in the AutoCAD. For the sake of the best precision, coordinate axes were reproduced as points arrays, fitted using the two endpoints. Unfortunately, no numeric data is available, so that graphical method is the only possible way to gather information. Results of calculations done are presented in tables 1 to 3. Abbreviations in the heading row: V – voltage, T – temperature, TT – treatment time, SWC – static water cut, D – default, SG – static gain, TC – time constant.



a - real tangent line; *b* – secant line

Fig. 5 – Two ways of drawing a tangent line to the green plot

Table 1 – Graphical identification results for varied voltage

V, U, kV	SWC, %	DV, U_d, kV	SG, K, % / kV	TC, T, s	
				Tangent	Secant
2	9,54	0	-10,23	88	174
4	6,52		-5,87	55	138
6	0,83		-4,86	16,8	-

Table 2 – Graphical identification results for varied temperature

T, t^o, °C	SWC, %	DT, t^o_d, °C	SG, K, % / °C	TC, T, s
40	2,18	20	-1,39	25,8
50	1,02		-0,97	17,4
60	1,02		-0,72	7,2

Table 3 – Graphical identification results for varied treatment time

TT, τ, min	SWC, %	DTT, τ_d, s	SG, K, % / min	TC, T, s
2	23,34	0	-3,33	-
5	7,03		-4,59	205,2
10	0,72		-2,93	21,6

To estimate quality of such approximation, we use integrated squared error (ISE) criterion, where experimental plot is the reference. Reference curves are replicated approximately using points corresponding to a given set of abscissa values. Since ISE is a relative criterion, which needs to be compared for different systems to be informative, we also provide a least-squares based approximation. LSQ is performed for two datasets:

1. initially chosen points on experimental curves (mentioned below just as LSQ);
2. linear interpolation of data with small step along the time axis (mentioned below as "least ISE", or LISE).

Using the Matlab environment, we calculated optimal static gain and time constant in terms of fitting graphically gathered data points with equal weights. For proper calculations, default control value (for each channel) is retained the same, and the difference of current control and default control is input into fitting function. Formula for step response in channel "control signal – residual water cut" is:

$$y(t) = 30 + K \cdot \left(1 - e^{-\frac{t}{T}}\right) \tag{4}$$

We also calculate y_s using the following formula:

$$y_s = 30 + x_s \cdot K, K < 0 \tag{5}$$

Results are in tables 4 to 6 (LSQ); in tables 7 to 9 (LISE); on fig. 6 to 8 (both). Plots are scaled logarithmically along time-axis for better readability.

Table 4 – LSQ approximation results for varied voltage

V, *U*, kV	SWC, %	DV, U_d, kV	SG, *K*, % / kV	TC, *T*, s
2	9,52	0	-10,24	130,89
4	6,55		-5,86	118,53
6	1,30		-4,78	14,75

Table 5 – LSQ approximation results for varied temperature

T, t^o, ºC	SWC, %	DT, t^o_d, ºC	SG, K, % / ºC	TC, T, s
40	2,82	20	-1,36	25,97
50	1,43		-0,95	14,06
60	1,11		-0,72	4,41

Table 6 – LSQ approximation results for varied treatment time

TT, τ, *min*	SWC, %	DTT, U_d, s	SG, K, % / *min*	TC, T, s
2	-21 247	0	-1 064	4 559 505
5	6,51		-4,70	154,88
10	1,31		-2,87	14,57

Table 7 – LISE approximation results for varied voltage

V, *U*, kV	SWC, %	SG, K, % / kV	TC, T, s
2	9,27	-10,36	147,62
4	6,25	-5,94	137,23
6	1,08	-4,82	15,51

Table 8 – LISE approximation results for varied temperature

V, t^o, ºC	SWC, %	SG, K, % / ºC	TC, T, s
40	2,63	-1,37	29,58
50	1,19	-0,96	14,81
60	1,12	-0,72	5,00

Table 9 – Minimal ISE approximation results for varied treatment time

V, τ, *min*	SWC, %	SG, K, % / *min*	TC, T, s
2	-31 354	-15 692	6 059 491
5	6,67	-4,67	144,12
10	1,08	-2,89	15,33

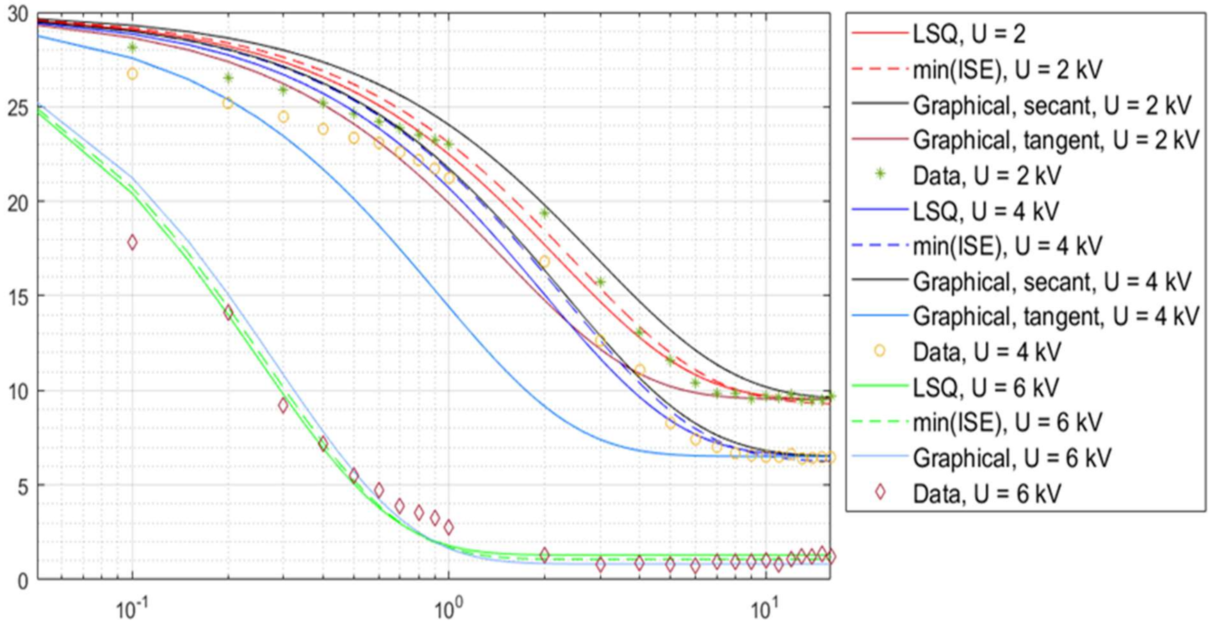


Fig. 6 – Data and approximations for varied voltage

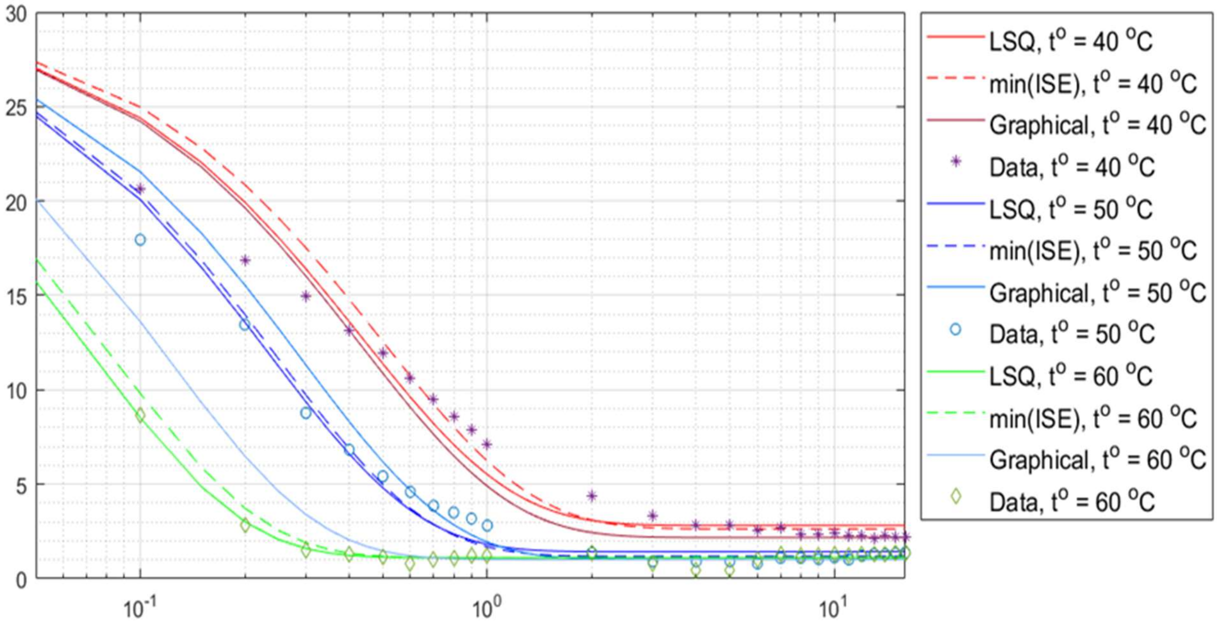


Fig. 7 – Data and approximations for varied temperature

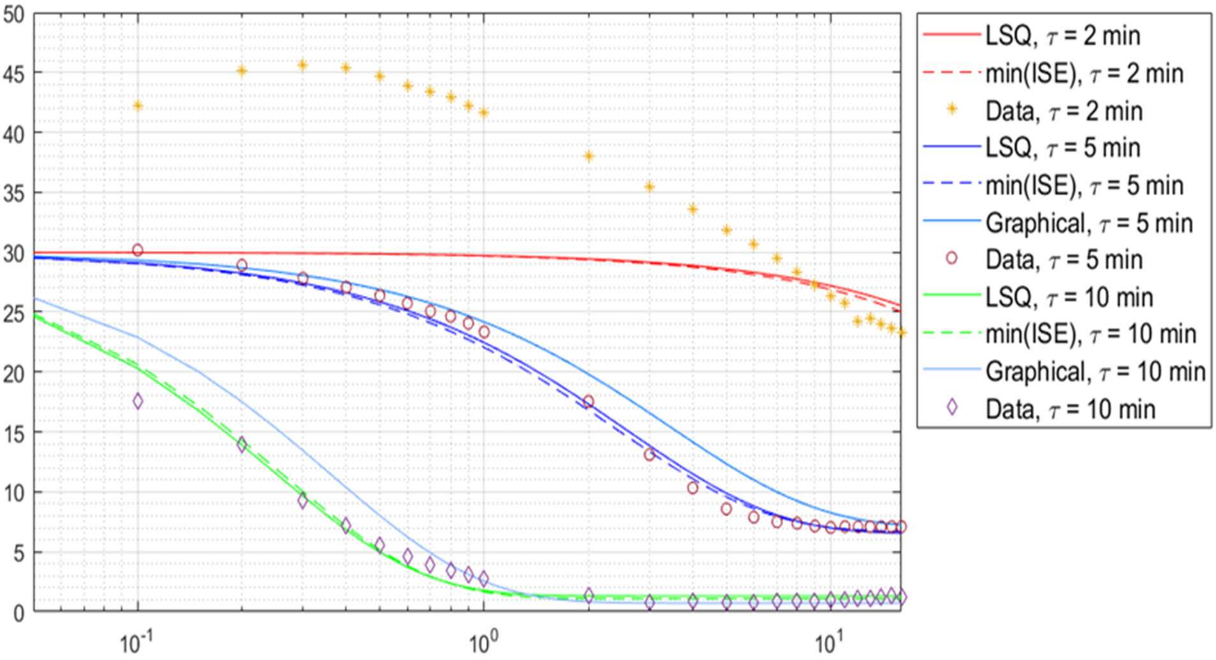


Fig. 8 – Data and approximations for varied treatment time

Table 10 – ISE criteria for varied voltage

V, *U*, kV	Tangent graphical	Secant graphical	LSQ	LISE
2	51,65	16,22	6,25	3,91
4	154,96	5,96	9,14	4,88
6	3,45	-	3,16	2,39

Table 11 – ISE criteria for varied temperature

T, *t*°, °C	ISE		
	Graphical	LSQ	LISE
40	14,61	10,20	9,04
50	3,57	3,07	2,20
60	4,53	1,86	1,58

Table 12 – ISE criteria for varied treatment time

TT, τ, *min*	ISE		
	Graphical	LSQ	LISE
2	-	429,18	427,93
5	68,51	6,25	5,07
10	9,18	3,17	2,37

Results of three approaches differ in static gain and time constant of the model. For clearness, all coefficients are collected in tables 13 and 14. Also, plots for variations of static gain and time constant are presented on figures from 9 to 11.

Table 13 – Static gain values

Method / Varied parameter and its current value	Graphical	LSQ	LISE
U = 2 kV	-10,23	-10,24	-10,36
U = 4 kV	-5,87	-5,86	-5,94
U = 6 kV	-4,86	-4,78	-4,82
t° = 40 °C	-1,39	-1,36	-1,37
t° = 50 °C	-0,97	-0,95	-0,96
t° = 60 °C	-0,72	-0,72	-0,72
τ = 2 *min*	-3,33	-1 064	-15 692
τ = 5 *min*	-4,59	-4,70	-4,67
τ = 10 *min*	-2,93	-2,87	-2,89

Table 14 – Time constant values (in seconds)

Method / Varied parameter and its current value	Graphical		LSQ	LISE
	tangent	secant		
U = 2 kV	88	174	130,89	147,62
U = 4 kV	55	138	118,53	137,23
U = 6 kV	16,8		14,75	15,51
t° = 40 °C	25,8		25,97	29,58
t° = 50 °C	17,4		14,06	14,81
t° = 60 °C	7,2		4,41	5,00
τ = 2 *min*	-		4 559 505	6 059 491
τ = 5 *min*	205,2		154,88	144,12
τ = 10 *min*	21,6		14,57	15,33

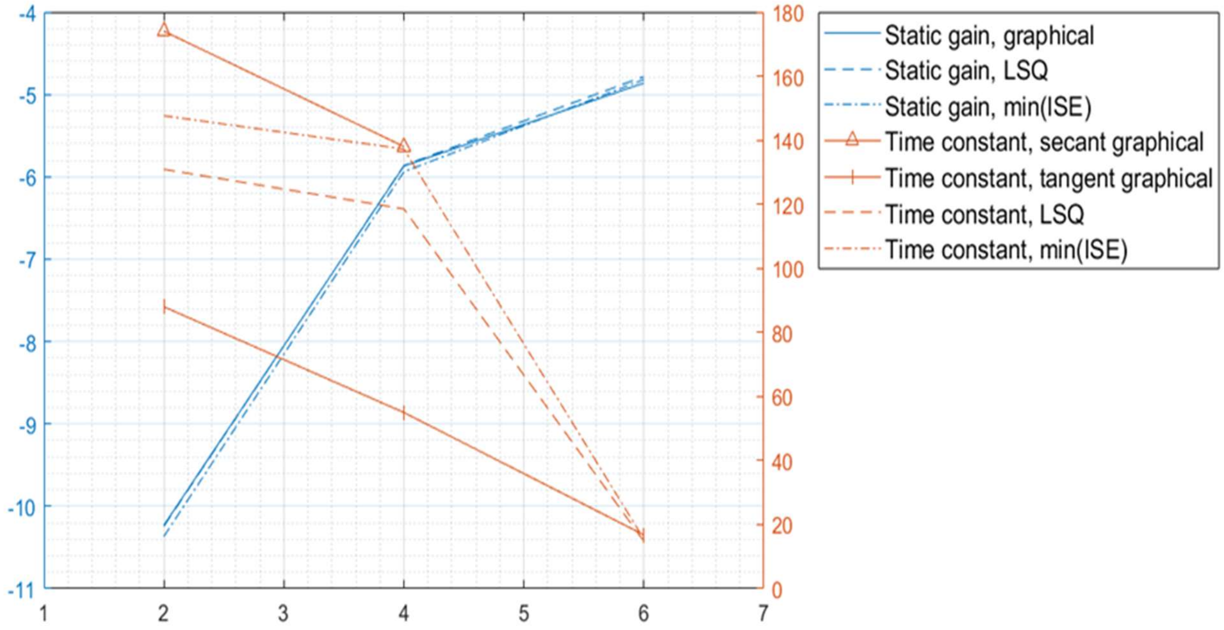


Fig. 9 – Static gain and time constant for varied voltage

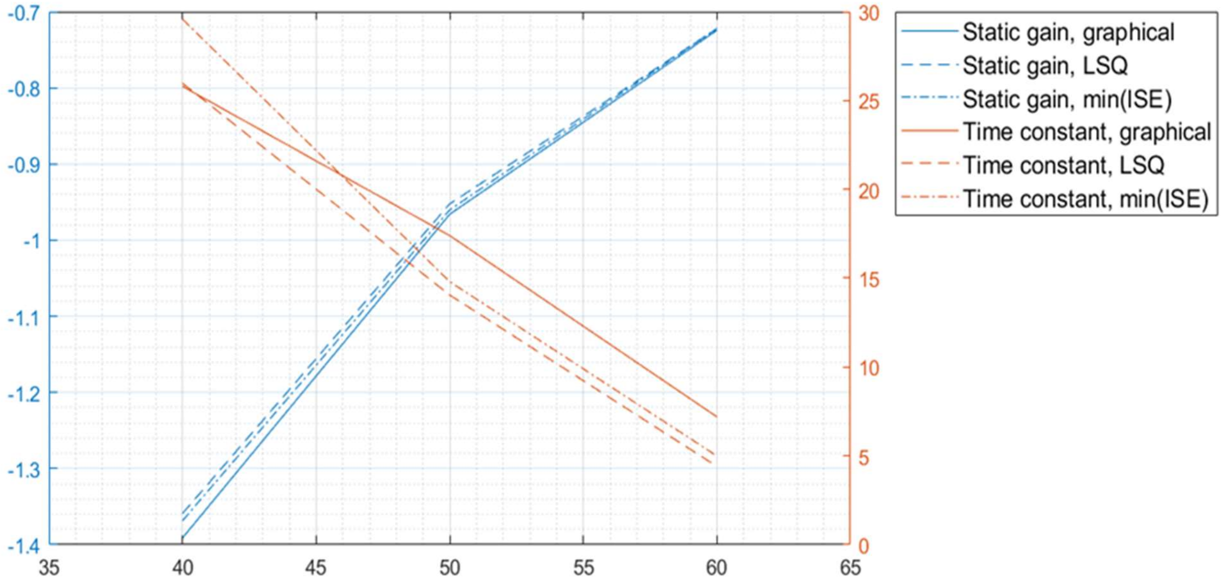


Fig. 10 – Static gain and time constant for varied temperature

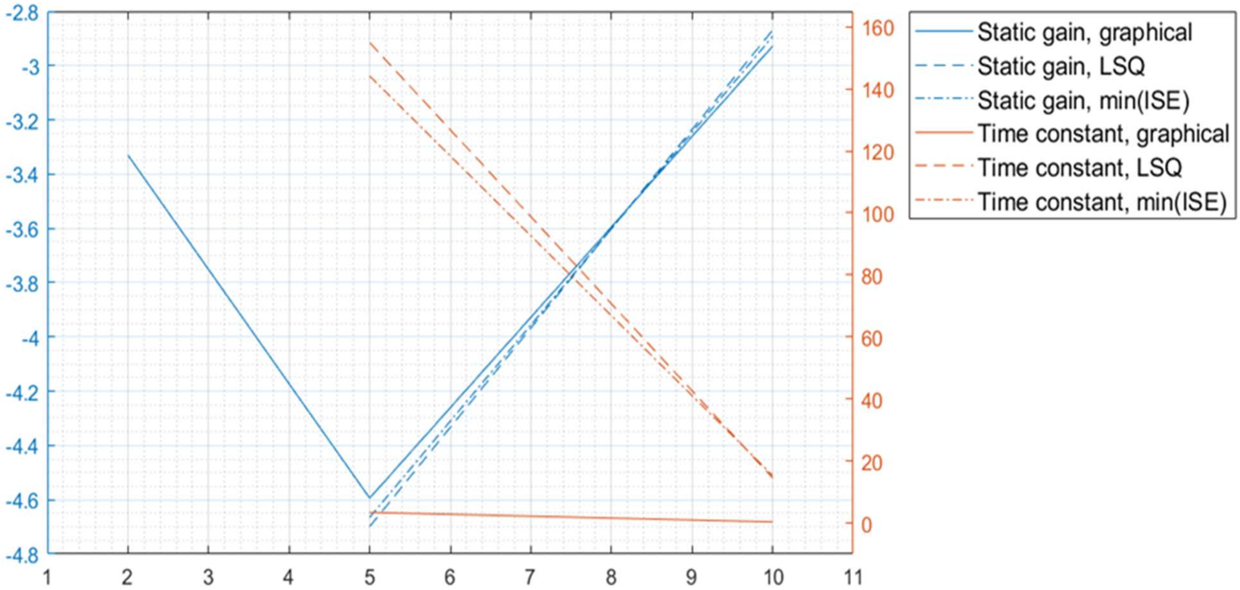


Fig. 11 – Static gain and time constant for varied treatment time

Values of static gain and time constant on the last plot (fig. 11) for LSQ and LISE approximations were omitted in order to save the scale.

From plots it is easy to see, that for all experiments values of static gain are quite close to each other for different approximations. That is supported by smooth and stable plots after reaching static process. On the other hand, difference between time constant is significant in all sets of experiments. However, for varied voltage and treatment time, time constant values obtained by different methods are closer to each other for larger values of control signal. For varied temperature, time constant deviation is roughly the same for all control signal values. Time constants for 2 kV and 4 kV, obtained via real tangent line, are too small, compared to time constants with secant line, which are much closer to LSQ and LISE approximations. This means that prediction of plant performance by means of coalescence rate is considerably worse than prediction of performance by mean of water removal. Still values obtained with LSQ and LISE fitting stay close enough to each other, while graphically obtained values deviates more. The same tendency is observed for gain.

Static gain and time constant on all plots are changing dramatically depending on parameters, which is an illustration of strong non-linearity of the object. Non-monotonicity of static gain of the plant for varied treatment time might be a result of too little sedimentation time, so that residual water cut could have not reached its actual static value. However, the last hypothesis needs further examining.

Conclusions. Transfer function of High Performance Electrostatic Coalescer was identified using three different methods: graphical approximation; least squares fitting for manually chosen point on plots; and least squares fitting for dense set of points, which emulates minimal integrated squared error fitting. Most experimental results exhibit HPEC as a plant with behaviour, close to linear system with parameters, depending on operation conditions.

Analysis of both procedure itself and numeric and plotted results shown the following:

1. graphically obtained approximation may have less value of ISE criterion than LSQ approximation with discrete pointset;
2. due to experiment peculiarities, there may be more than one possible graphical approximation;
3. both LSQ and LISE approximations resemble in numeric results each other more than any of them and graphical approximation do;
4. although LISE approximation is better than LSQ in terms of ISE criterion, LSQ is seemingly better in predicting the rise time;
5. some measurement results are impossible to fit with first-order transfer function;
6. with larger control signal values, electrocoalescence unit shows more “linear-like” behaviour: time constant values in different approximations are getting closer to each other, so that response plot is getting closer to response plot of a real first-order system; plot of static gain becomes less steep.

As a consequence of the facts mentioned just above, it is not recommended to rely on graphical approximation method since it is much more sensitive to noises and plot inaccuracies. In addition to that, it includes human factor. The best fitting method is ISE minimization. It is practically useful because it might be easily approximated by point LSQ fitting with dense set of points, uniformly distributed along the time segment investigated.

Method used in the current research may be used for experimental identification of an electrocoalescence unit transfer function in other cases. Dependencies obtained may then be used for linearization in the neighbourhood of a static point. After linearization, synthesis of a PID or other type of linear controller becomes possible.

Peospects of further research. In order to fulfill needs of automation system developing process, results of the current research should be completed with linearization procedure in a neighbourhood of a chosen static point. This will allow to design a typical linear (for example, PID) controller using such a model. As far as experimental plant is rather different from an industrial one, similar calculations should be provided for data, collected from an industrial plant. Some possible enhancements of the approach are to be examined. For example, identification of static gain and time constant may be separated into a consequent procedure: one calculates a horizontal asymptote using only data from static process, and then time constant is obtained by approximation with given gain instead of undefined one, as it was done in this paper.

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МОДЕЛЮВАННЯ ЕЛЕКТРОДЕГІДРАТОРА ВИСОКОЇ ШВИДКОДІЇ НА ОСНОВІ ЕКСПЕРИМЕНТАЛЬНИХ ДАНИХ

Дотепер в літературі немає опису моделі електродегідраторів нафти за типом «вхід – вихід», які придатні для розробки модельно-орієнтованої системи автоматичного керування. Метою роботи є порівняння різних способів отримання наближеної передавальної функції електродегідратора на основі графічних експериментальних даних.

Для опису електродегідратора було вибрано аперіодичну ланку першого порядку з часовим запізненням, невідомими параметрами якої є коефіцієнт підсилення та стала часу. Час запізнення визначено умовами проведення експерименту, а саме тривалістю перебування емульсії в електричному полі. Для визначення коефіцієнтів використано три методи: графічна апроксимація на основі геометричного змісту вказаних параметрів; апроксимація методом найменших квадратів; апроксимація методом мінімізації інтегралу квадратичної похибки моделі. Для втілення останніх двох методів з графіків перехідних характеристик вручну вибрано дискретний набір точок, координати яких використано для подальших обчислень.

Всі три методи дають приблизно однакові результати для статичного підсилення. Графічний метод визначення сталої часу менш ефективний через неточність проведення дотичної та шуми на графіку. Окрім того, стала часу, визначена графічно, сильно залежить від початкового кута нахилу перехідної характеристики, який змінюється в деяких випадках немонотонно, що не є властивим для аперіодичної ланки першого порядку. Наприклад, для напруги 2 кВ і 4 кВ кут нахилу є збільшеним на початковій ділянці, що дає надто малу сталу часу: 88 с для 2 кВ, 55 для 4 кВ. Метод найменших квадратів для цих двох випадків дав сталі часу 130,89 с і 118,53 с відповідно. Заміна справжньої дотичної на січну не вирішує такої проблеми, оскільки для підтвердження точності необхідно щоразу будувати перехідну характеристику, що невиправдано збільшує час на обробку результатів. Проведені січні дали значення сталої часу 174 с і 138 с для 2 кВ і 4 кВ відповідно, що теж не є задовільним результатом. Найбільшу загальну точність показує метод мінімізації інтегральної похибки, проте метод найменших квадратів точніше передбачає швидкодію, що пов'язано зі збільшеною кількістю вибраних точок на початковій ділянці перехідної характеристики. Для порівняння: з напругою 2 кВ, графічний метод із дотичною та січною, а також метод найменших квадратів і найменшого інтегрального критерію мають інтеграл квадрату похибки 51,65, 16,22, 6,25 і 3,91 відповідно. Хоча для кожного окремого експерименту апроксимація об'єкта аперіодичною ланкою першого порядку забезпечує прийнятну точність, значення коефіцієнту підсилення та сталої часу суттєво відрізняються залежно від умов перебігу процесу. Наприклад, при зміні напруги між електродами від 2 кВ до 6 кВ коефіцієнт підсилення за цим каналом змінюється (за результатами методу найменшого інтегрального критерію) з -10,36 до -4,82 (більш, ніж у два рази), а стала часу з 147,62 до 15,51 (на порядок). В усіх дослідах при збільшенні значення сигналу керування (незалежно від каналу) зменшується коефіцієнт підсилення (за модулем) і стала часу (збільшується швидкодія). Також зменшується прояв нелінійності поведінки системи, і збільшується збіжність результатів різних методів апроксимації. Так, за напруги в 6 кВ сталі часі, *отримана графічним методом, методом найменших квадратів та найменшого інтегрального критерію, наступні: 16,8 с; 14,75 с; 15,51 с. Так само, зі зменшенням сигналу керування точність різко падає аж до повної неадекватності обраної моделі. За нульового (для напруги й температури) або за малого порівняно з іншими значення (для часу перебування) поведінку системи неможливо апроксимувати аперіодичною ланкою першого порядку з від'ємним коефіцієнтом підсилення.*

В дослідженні вперше отримано передавальну функцію електродегідратора за наступними каналами керування: напруга між електродами, температура нафти, час перебування.

Ключові слова: *математичне моделювання, ідентифікація, передавальна функція, аперіодична система першого порядку з запізненням, метод найменших квадратів, критерій інтегральної квадратичної похибки.*

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