# THE PARAMETERS OF CLEANING A CIP SYSTEM AFFECTED ENERGY CONSUMPTION AND CLEANING EFFICIENCY OF THE PLATE HEAT EXCHANGER

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This paper presents a study on the effect of cleaning factors on the energy consumption of the cleaning process in a CIP system, and the correlation between single components of electricity necessary to perform this process and the cleanliness degree obtained. Studies were carried out in a laboratory cleaning station, wherein a plate heat exchanger contaminated with hot milk was included. The research program was developed according to a 5-level statistical plan. Based on the results, obtained with Experiment Planner 1.0, a regression function of energy requirement considering variables such as: cleaning time, temperature and flow rate of the cleaning liquid via the cleaned exchanger has been developed. Describing this relationship, linear and quadratic functions with double interactions were used. Significance level for the analysis was established at $\alpha = 0.05$. Correlation analysis between components of the electricity necessary to perform the cleaning process (pump drive and heating of the cleaning agent) and the resulting degree of cleaning of heat exchanger plates was performed.

Keywords: cleaning, CIP system, energy consumption, cleaning parameters, cleanliness, cleaning efficiency

## 1. INTRODUCTION

The food industry is a major consumer of water and energy. Furthermore water and energy are interrelated with wastewater production (Krzemińska et al. 2013). The demand for agro food processing facilities for water and energy is dependent on many factors (Kowalczyk and Karp, 2005; Steinhoff-Wrześniewska et al., 2013; Williams and Anderson, 2006; Wojdalski et al., 2013). The basic ones include technology of food processing, technical equipment, degree of automation and mechanization of production operations, thermophysical properties of materials, requirements for products, magnitude and structure of production and its organization (Bunse et al., 2011; Marchini et al., 2014; 2015; Wojdalski and Dróżdż, 2012) and related with those the operations of cleaning and disinfection of machines and production equipment. Some reports indicate that the cleaning processes in food industry are energy-intensive processes and that in the food industry they require even about 13.5 - 14% of the total process energy consumption (Neryng et al., 1990; Pawełas, 2010; Rad and Lewis, 2014). This consumption primarily results from the operation conditions of the CIP cleaning station, type and size of the objects subjected to cleaning and the choice of cleaning agents (Piepiórka-Stepuk et al., 2016; Ramirez et al., 2006; Wojdalski et al., 2013). Studies conducted by many authors on cleaning of milk installations suggest that energy requirement of cleaning process in flow mainly results from the necessity of heating a large volume of cleaning agents in storage tanks (even up to

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95 °C) and maintaining their appropriate temperature throughout the cleaning time (Berlin et al., 2007; Diakun et al., 2012; Eide et al., 2003). Electricity consumption for this aspect of the cleaning process exceeds twelve times that necessary to force the flow of cleaning agents. Other studies regarding the selection of optimum cleaning conditions in the CIP system demonstrate that it is possible to increase the degree of cleanliness of washed installation with a simultaneous reduction of energy consumed (Jude and Lemaire, 2014; Piepiórka-Stepuk et al., 2016). For the process optimization is necessary to develop a function which is a mathematical description of this process containing the variable factors. In the available literature, there are no reports on the theoretical and analytical modeling describing the effect of cleaning agents in flow (time, temperature and flow rate) on energy intensity of this process. Moreover, there are no experimental results, based on which we could infer the character of interactions between these factors and energy consumption of the process. The objective of the study was to develop a regression function describing the relationship between the amount of energy necessary to perform the process of cleaning of a plate heat exchanger and different factors, such as time, temperature and flow rate.

## 2. MATERIALS AND METHODS

### 2.1. Construction of research station and research program

Experiments were conducted using a two-tank cleaning station in the CIP system (1, 2) (Fig. 1), wherein S4 IT PN 10 (1) (Sondex) plate heat exchanger was included (Table 1). One of the tank installations (2) had a built-in heater of 3 kW power and thermal insulation, which enabled the preparation of cleaning solutions of a specified temperature and restricted heat loss into the environment. Heater power supply accomplished through a thermostatic control system which allowed heating and stabilization of liquid temperature in the tank. Water of different temperatures was prepared in this tank.
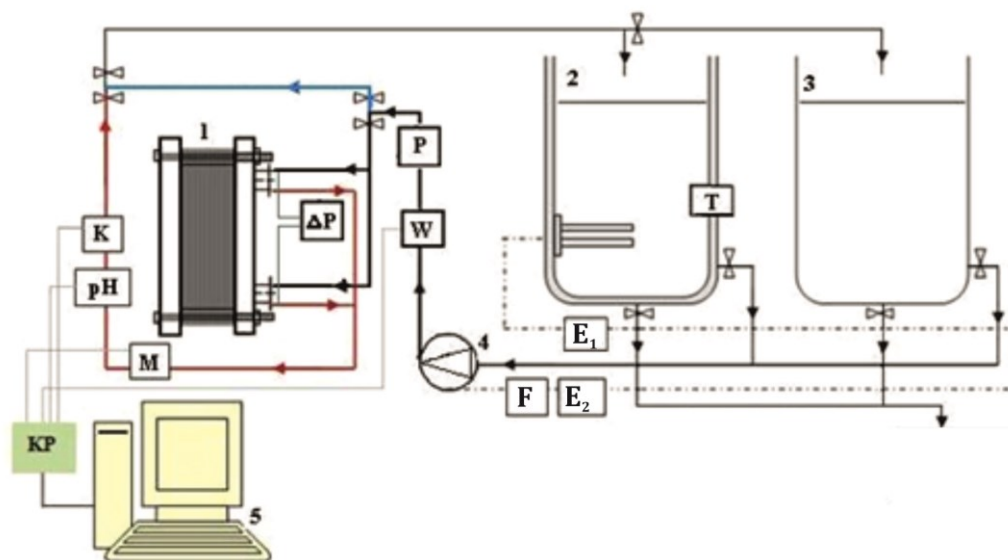


Fig. 1. Scheme of a laboratory CIP station. Legend: *K* – conductivity meter; *pH* – pH-meter; *M* – turbidity meter; *KP* – computer card; *P* – pressure gauge; $\Delta P$ – pressure drop between inlet and outlet of the heat exchanger; *W* – flow rate meter; *F* – inverter; $E_1$ – consumed energy meter used to power the pump; $E_2$ – consumed energy meter used to heat the cleaning liquid; *T* – thermometer; 1 – object to be cleaned (plate heat exchanger); 2 – insulated tank with a heater; 3 – non-insulated tank; 4 – pump; 5 – computer

Table 1. Main geometrical characteristics of the plate heat exchanger used in the study

| Geometrical characteristics | Symbol | Unit | Value |
|---|---|---|---|
| Effective length of the plate | $L_w$ | m | 0.381 |
| Effective width of the plate | $L_s$ | m | 0.111 |
| Area of a single plate | $A = L_w \cdot L_s$ | m² | 0.042 |
| Area of heat transfer | $A_c$ | m² | 0.378 |
| The largest distance between plates | $b$ | m | 0.008 |
| Mean distance between the plates | $c = (b/2)$ | m | 0.004 |
| Surface area of the flow cross-section | $P_{str} = cL_s$ | m² | 0.0005 |
| Wetted perimeter | $Ob_c = 2c + 2L_s$ | m | 0.23 |
| Total number of plates in the heat exchanger | $N_p$ | items | 11 |
| Number of channels in the plate heat exchanger | $N_c = (N_p - 1)/2$ | items | 5 |
| Hydraulic diameter of the channel | $d_{ch}$ | m | 0.009 |
| Corrugation angle | $\beta$ | ° | 60 |
| Type of plates | *Straight - flow* | | |

Table 2. Cleaning programs used in the research

| Level of the research plan | Variables | | | Reynolds number |
|---|---|---|---|---|
| | $T$ (min) | $T$ (°C) | $u_c$ (m·s⁻¹) | $Re$ (-) |
| 1 | 32 | 24 | 0.45 | 4420 |
| 2 | 98 | 24 | 0.45 | 4420 |
| 3 | 32 | 66 | 0.45 | 9251 |
| 4 | 98 | 66 | 0.45 | 9251 |
| 5 | 32 | 24 | 0.65 | 6384 |
| 6 | 98 | 24 | 0.65 | 6384 |
| 7 | 32 | 66 | 0.65 | 13362 |
| 8 | 98 | 66 | 0.65 | 13362 |
| 9 | 120 | 45 | 0.55 | 8187 |
| 10 | 10 | 45 | 0.55 | 8187 |
| 11 | 65 | 80 | 0.55 | 13494 |
| 12 | 65 | 10 | 0.55 | 3786 |
| 13 | 65 | 45 | 0.75 | 11164 |
| 14 | 65 | 45 | 0.35 | 5210 |
| 15 | 65 | 45 | 0.55 | 8187 |
| 16 | 65 | 45 | 0.55 | 8187 |
| 17 | 65 | 45 | 0.55 | 8187 |
| 18 | 65 | 45 | 0.55 | 8187 |
| 19 | 65 | 45 | 0.55 | 8187 |
| 20 | 65 | 45 | 0.55 | 8187 |

The cleaning system was equipped with an impeller pump (4) and meters for measuring the quantities characterizing the flow, i.e. flow rate in the pipeline (*W*), pressure (*P*) and the pressure drop between the inlet and the outlet of the heat exchanger (Δ*P*). Furthermore, the system had sensors which registered changes in the properties of the washing liquid, i.e. temperature (*T*), turbidity (*M*), conductivity (*K*), pH (*pH*), electricity required to heat the washing liquid (E$_1$-PM 390 meter, Elektro-Trading company) and and to power the pump (E$_2$-C-52 three-phase electricity meter, Inventor company). All the process data were recorded (5). The cleaning process was carried out only with pure water. The plan of the study covered the cleaning process including the factors for which variability was within the range:

- cleaning time – $t = 10 \div 120$ min;
- mean flow rate between plates of the heat exchanger calculated based on the flow rate measured in the pipeline – $u_c = 0.35 \div 0.75$ m·s$^{-1}$;
- temperature of the washing liquid – $T = 10 \div 80$ °C.

The research program was developed according to a 5-level statistical plan $2^3 + 2 \times 3 + 6$, based on which we could obtain an experiment matrix presented in Table 2.

### 2.2. Evaluation of energy consumption of the process and cleaning efficiency

For test purposes, a single measuring cycle covered milk contamination of plates, installation of the heat exchanger and cleaning in flow with simultaneous measurement of energy requirement of pump drive (*E$_{Pi}$*) and heating the cleaning agent *(E$_{Gi}$)*. Total energy consumption of the cleaning process was calculated according to Eq. (1) (Wojdalski et al., 2012).

$$E_C = E_{Pi} + E_{Gi} \text{ (kWh)} \tag{1}$$

After completion of the cleaning process, the exchanger was disassembled and using the *Clean-Trace$^{TM}$ Surface Protein Plus* swab tests based on Cu$^{2+}$-induced color reaction and protein complexes, information on the amount of residual protein contaminants was obtained (Piepiórka-Stepuk, 2012). The degree of purity was determined on a 0–10 point scale, in which 0 denoted an initial contamination of plates with milk, and 10 points - desired purity of plates (lack of any contaminants). All plates in the exchanger were evaluated, in five identical areas on the plate of 5.0 cm × 5.0 cm in diameter. Based on test results, the overall average cleanliness of the heat exchanger plates (*J$_M$*) was determined from Eq. (2).

$$J_M = \frac{\sum (J_{MOi})}{m} \tag{2}$$

Studies were carried out in triplicate for each set of factor values. After collecting the experimental study results, the Pearson correlation coefficient which defines a linear relationship between the energy consumption (*E$_{Pi}$*; *E$_{Gi}$*) and the total consumption (*E$_C$*) in the cleaning process and the purity of plate exchanger (*J$_M$*), was calculated. Furthermore, for each cleaning program, cleaning efficiency (*C$_E$*) could be calculated according to Eq. (3). It was defined as the increase of cleaning degree in 1 kWh of energy.

$$C_E = \frac{J_M}{E_C} \left( \frac{1}{\text{kWh}} \right) \tag{3}$$

### 2.3. Methodology for the development of regression function of energy consumption in the cleaning process

The obtained results constituted a basis to develop a regression function describing the energy consumption of the cleaning process in the CIP system of the plate heat exchanger in a function of

time, temperature and average flow rate in the gap between $E_C$ plates ($t$, $T$, $u_c$). To describe the proposed relationship, linear and quadratic functions with double interactions (4) were proposed. Linear components determine the trend of linear character of interactions of single factors on the energy intensity of the process, while the square components can be used to determine the optima of interactions for each factor, deviations from non-linearity and extremes.

$$\breve{\bar{Y}} = \breve{\bar{E}}_C = k_0 + k_1 t + k_2 T + k_3 u_c + k_{12} tT + k_{13} tu_c + k_{23} Tu_c + k_{11} t^2 + k_{22} T^2 + k_{33} u_c{}^2 \qquad (4)$$

Calculations were done in the Experiment Planner 1.0 software, according to the method described by Kukiełka (2002) and Diakun et al. (2012) for a significance level of $\alpha = 0.05$. Based on the obtained results, ten unknown coefficients of the model equation were determined; $k_0$; $k_1$; $k_2$; $k_3$; $k_{12}$; $k_{13}$; $k_{23}$; $k_{11}$; $k_{22}$; $k_{33}$. Results of the experimental study were subjected to statistical analysis according to the following algorithm:
- elimination of results affected by a gross error;
- calculation of inter-row variability and standard deviation;
- evaluation of variance homogeneity in the sample;
- calculation of the coefficients in the regression function;
- statistical analysis of the regression function;
- evaluation of significance of multidimensional correlation coefficient;
- assessment of the adequacy of mathematical model;
- regression function decoding;
- determination of the confidence intervals.

The resulting equation describes the function of the energy consumption of plate heat exchanger cleaning. The obtained function was presented in a graphical form as a configuration of different factors.

## 3. RESULTS AND DISCUSSION

### 3.1. Analysis of regression model describing energy consumption in the cleaning process

Based on study results obtained and statistical analysis, we developed a regression function describing the total energy consumption in the cleaning process. Multidimensional correlation coefficient for the adopted class of mathematical model was $R = 0.993$. After taking into account non-significant factors which were highlighted in the equation by a continuous line, the regression function as a second degree polynomial with double interactions, takes the following form encoded as Eq. (5):

$$\breve{\bar{Y}} = \breve{\bar{E}}_c = 4.966 + 1.198\breve{\bar{x}}_1 + 3.221\breve{\bar{x}}_2 + 0.1\breve{\bar{x}}_3 + 0.567\breve{\bar{x}}_1\breve{\bar{x}}_2 +$$
$$- 0.125\breve{\bar{x}}_1\breve{\bar{x}}_3 - 0.502\breve{\bar{x}}_2\breve{\bar{x}}_3 + 0.142\breve{\bar{x}}_1{}^2 + 0.476\breve{\bar{x}}_2{}^2 - 0.005\breve{\bar{x}}_3{}^2 \qquad (5)$$

The *F-Snedecor* test showed that there were no grounds to reject the hypothesis about the significance of the multidimensional correlation coefficient and there were no grounds to reject the hypothesis on the truth of the regression coefficients. The critical value of the *F-Snedecor* test for the analysis was estimated at $F_{kr} = 3.02$, resulting in the inequality $F_E = 86.68 > F_{kr} = 3.02$. After decoding, the function describing the energy consumption of cleaning the plate heat exchanger is described in the following form:

$$\breve{\bar{E}}_c = -6.62 + 0.002\bar{t} + 0.133\bar{T} + 12.8\bar{u}_c + 0.0008(\bar{t}\bar{T}) +$$
$$- 0.038(\bar{t}\bar{u}_c) - 0.239(\bar{T}\bar{u}_c) + 0.0001(\bar{t}^2) + 0.0011(\bar{T}^2) \qquad (6)$$

Considering confidence interval for the obtained function (7), the function is described as (8):

$$\Delta \overset{\approx}{\overline{E}}_c = \pm 0.0484 \sqrt{\begin{aligned} &0.123\left[\left(\frac{t-65}{27.5}\right)^4+\left(\frac{T-45}{17.5}\right)^4+\left(\frac{u_c-0.55}{0.1}\right)^4\right]+ \\ &0.246\left[\left(\frac{t-65}{27.5}\right)^2\left(\frac{T-45}{17.5}\right)^2+\left(\frac{t-65}{27.5}\right)^2\left(\frac{u_c-0.55}{0.1}\right)+\left(\frac{T-45}{17.5}\right)^2\left(\frac{u_c-0.55}{0.1}\right)^2\right]+ \\ &0.036\left[\left(\frac{t-65}{27.5}\right)^2\left(\frac{T-45}{17.5}\right)^2+\left(\frac{u_c-0.55}{0.1}\right)^2\right]+0.217 \end{aligned}} \tag{7}$$

$$\overset{\approx}{\overline{E}}_C = \overset{\approx}{\overline{E}}_C \pm \Delta \overset{\approx}{\overline{E}}_C \tag{8}$$

The obtained function describes the energy consumption of the cleaning process of the plate heat exchanger in flow, under certain conditions and research scope adopted. Minus introduced in the beginning denotes a certain inconsistency, because when substituting zero values with $t$, $T$, $u_c$ factors, a negative value of energy is obtained. It results from the fact that the lowest temperature of the cleaning agent, for which the studies were carried out, was 10 °C and therefore the developed equation is true only within the tested range. Cleaning below this temperature value is consistent. A similar situation occurs in terms of square of the temperature and the time. Energy consumption during the process should be linear, which means that electricity consumption should be proportional to the duration of a given operation or process. From the resulting function it can be concluded however, that time in the quadratic function is also important in cleaning processes. It results from a constant need to heat the cleaning solutions during the process in order to maintain the cleaning temperature at the assumed level. The longer the process of cleaning, the more frequent the heater was run to compensate for heat losses into the environment and maintain thermal conditions. In consequence, it leads to deviation of the function from non-linearity. As a result of statistical analysis, it can be concluded that within the tested range, the square of the flow rate ($u_c^2$) on energy requirement ($E_C$) is non-significant. The impact of cleaning parameters on energy consumption of the process was graphically presented in Figure 2, as a configuration of two variables. Factors which are not present on the plots have fixed, central values of the research program: $t = 65$ min; $T = 45$ °C; $u_c = 0.55$ m·s$^{-1}$.
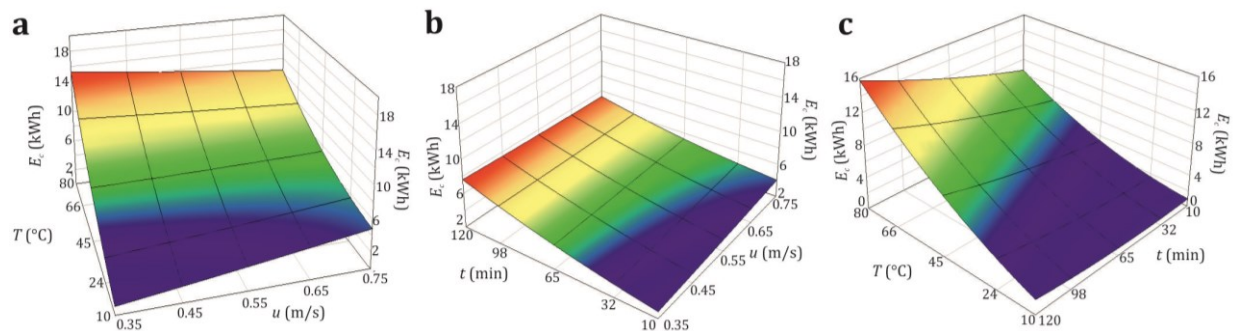


Fig. 2. Total energy consumption $E_c$ as a function of temperature ($T$), flow rate ($u_c$) and time ($t$): a – relationship between energy consumption as a function of temperature and flow rate; b – relationship between energy consumption as a function of time and flow rate; c – relationship between energy consumption as a function of temperature and time

The graphical form of the function confirms that energy consumption of the process increases with temperature of the cleaning factor, which is consistent with previous reports (Diakun et al., 2012). This relationship for the cleaning time equal to $t = 65$ minutes is linear with maximum for $T = 80$ °C (Fig. 2a). Increase in a flow rate of the cleaning agent affects energy consumption of the process to a small extent (Fig. 2b). However, a different effect is exerted by cleaning time which is related to

temperature up to which cleaning agents are heated. At low temperatures, extension of the cleaning time does not affect the overall energy increase, while for high temperatures, it leads to its increase by almost 100% (Fig. 2c).

It mainly results from cooling of the cleaning agent with time, resulting from temperature difference between the tank and the heated liquid, as well as cooling by the cleaned objects, which occurs immediately after starting the installation. As a consequence of cooling, the cleaning agent was continuously heated in order to maintain the temperature at an assumed level, which affected the form of equation.

### 3.2. Analysis of the efficiency of cleaning in relation to total energy requirement

In Fig. 3, we summarize the obtained values of the energy requirement $(E_{Pi}; E_{Gi})$ and total energy consumption $(E_C)$ in cleaning process for each trials of the research program according to Table 2.
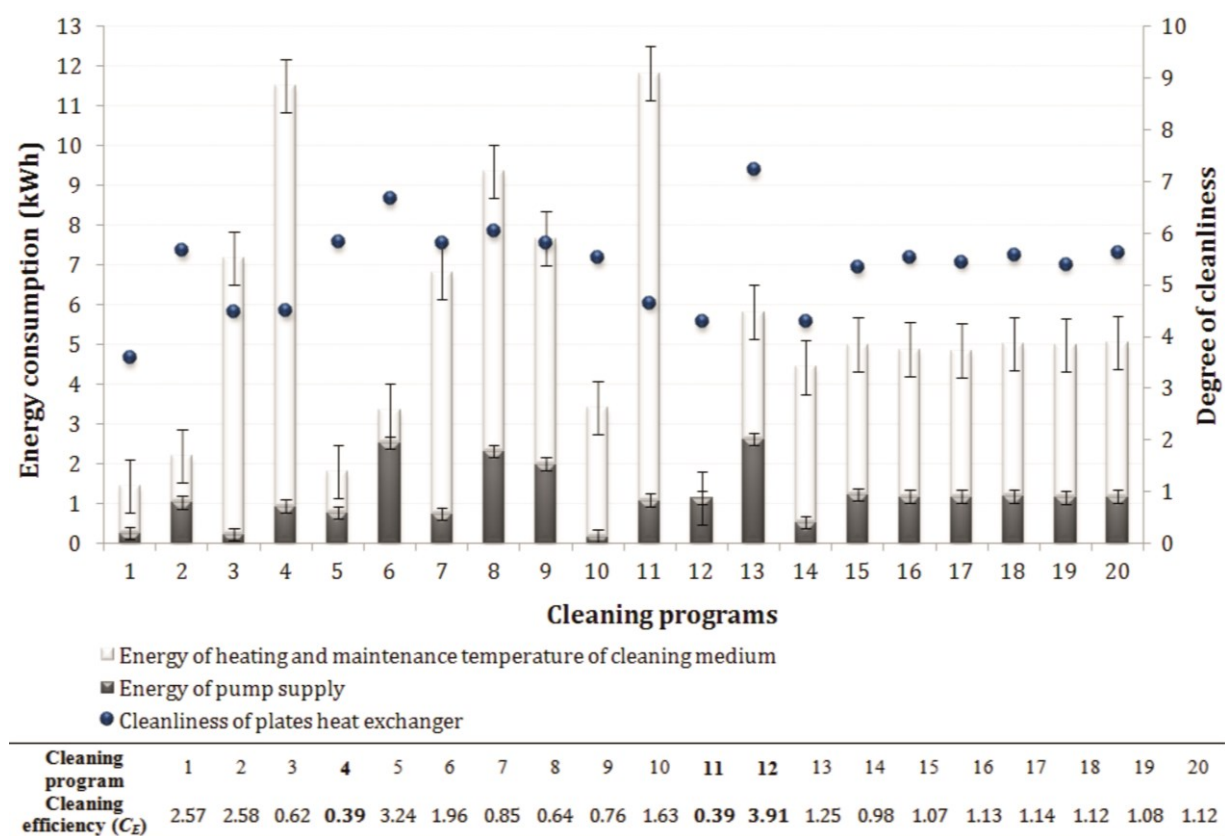


| Cleaning program | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cleaning efficiency $(C_E)$ | 2.57 | 2.58 | 0.62 | **0.39** | 3.24 | 1.96 | 0.85 | 0.64 | 0.76 | 1.63 | **0.39** | **3.91** | 1.25 | 0.98 | 1.07 | 1.13 | 1.14 | 1.12 | 1.08 | 1.12 |

Fig. 3. The degree of cleaning of plate heat exchanger for single components $(E_{Pi}$ and $E_{Gi})$ and the total $(E_C)$ energy requirement in particular trials of the research program: a – electricity necessary to heat and maintain temperature of the cleaning liquid; b-electricity necessary to drive the pump; c-overall average purity of plates of the heat exchanger.

The conducted studies demonstrated that within the programs, in which the highest total electricity consumption (program 4 and 11-about 12 kWh) was reported, no satisfactory results of cleaning were obtained. The maximum cleanliness of the surface of heat exchanger plates for these cleaning programs, reached the value of less than 5 points. For those programs the least cleaning efficiency a about 0.39 was achieved. A similar effect of cleaning (between 4÷5 points) was obtained for the program 12, for which we reported the lowest total energy consumption (1 kWh) related solely to the operation of the impeller pump during cleaning. In this program, the highest coefficient of cleaning

efficiency was achieved (3.91). The value of the Pearson correlation coefficient for the total energy consumption $(E_C)$ and obtained purity of exchanger plates $(J_M)$ was $r = 0.01$, what indicates a lack of relationship between the variables which were analyzed. The obtained results also demonstrated that the main reason for high energy consumption in the process of cleaning of the dairy installations, is high temperature of cleaning agents in the range of $65 - 85\ °C$ (Rad and Lewis, 2014; Ramirez et al., 2006), although according to presented results, this factor does not improve the efficiency of removal of milk residues from the exchanger plates (programs 3, 4, 11). Similar results were obtained by Diakun et al. (2012) and Wojdalski et al. (2013). The Pearson correlation coefficient for these variables $(E_{Gi};\ J_M)$ was $r = -0.17$, indicated a negative correlation between the analyzed variables. When interpreting this result, we can conclude that with increase in the amount of electricity consumed for heating rinsing water, the efficiency of removal of milk residues from the installation decreases. Properties of milk residues may be an explanation for that phenomenon as they are not dissolved in high temperature of the cleaning liquid (Almecija et al., 2009; Changani et al., 1997; Fryer et al., 2006). Analysis of the study results also showed that with an increase in the electricity necessary for the operation of the impeller pump, effectiveness of the heat exchanger cleaning is increasing. The Pearson correlation coefficient for these variables $(E_{Pi};\ J_M)$ was positive and accounted for $r = 0.74$. This was confirmed by the study results obtained in the cleaning programs 6 and 13, in which electricity consumption to force the flow of cleaning liquid was the highest (about 2.5 kWh) with the highest cleaning efficiency of the heat exchanger (about 7 points). The cleaning efficiency coefficients for these programs were in range of $1.25 - 1.96$. Thus, increase in the flow rate during the cleaning process not only improves the cleaning efficiency, as observed by other authors (Goode et al., 2010; Fryer et al., 2006), but also affects the reduction of costs associated with performance of the process with simultaneous decreasing of the temperature of cleaning agents.

## 4. CONCLUSIONS

- Energy consumption in the cleaning process is mainly related to heating the cleaning media and maintaining them at a certain level.

- The obtained results indicate that in case of milk residues which are formed during high-temperature treatment of milk on plates in heat exchangers, high temperature of rinsing water does not always provide a better end result of the cleaning.

- Negative correlation was reported between the requirement for the electricity associated with heating of the cleaning liquid and the efficiency of removal of milk residues from the plates of the heat exchanger.

- Requirement for energy related to forcing the flow is much lower in comparison to the requirement for heating the washing liquid.

- Flow rate is a cleaning factor which leads to the improvement of the cleaning quality with its increase.

- There is a high correlation ($r = 0.74$) between the energy necessary to drive the pump and the efficiency of washing plates of the heat exchanger contaminated with milk.

- In the ecological and safety aspects of food production, it is advised to use possibly high flow rates of the cleaning media ($u_c = 0.75$; $Re \approx 11\ 000$) at the cost of very high temperature (T = 80 °C) and very long cleaning time ($t = 120$ min).

## SYMBOLS

| | |
|---|---|
| $m$ | sample size (the product of the number of areas on a single plate and the number of plates subjected for evaluation): $m = 25$ |
| $t$ | cleaning time, min |
| $u_c$ | mean flow velocity per channel, m·s$^{-1}$ |
| $C_E$ | cleaning efficiency, kWh$^{-1}$ |
| $E_{Gi}$ | energy of heating and temperature maintenance of cleaning agents, kWh |
| $E_{Pi}$ | pump power supply, kWh |
| $E_C$ | total energy consumption in the cleaning process, kWh |
| $J_M$ | effectiveness of cleaning of the heat exchanger plates |
| $J_{MOi}$ | cleanliness of a single area on subsequent plates of the heat exchanger |
| $T$ | temperature of the cleaning liquid, °C |
| $Re$ | Reynolds number |

## REFERENCES

Almecija M.C., Martinez-Ferez A., Guadix A., Paez M.P., Guadix E.M., 2009. Influence of the cleaning temperature on the permeability of ceramic membranes. *Desalination,* 245, 708–713. DOI: 10.1016/j.desal.2009.02.041.

Berlin J., Sonesson U., Tillman A.M., 2007. A life cycle based method to minimize environmental impact of dairy production through product sequencing. *J. Cleaner Prod.*, 15, 347–356. DOI: 10.1016/j.jclepro.2005.07.019.

Bunse K., Vodicka M., Schönsleben P., Brülhart M., Ernst F.O., 2011. Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature. *J. Cleaner Prod.*, 19, 667–679. DOI: 10.1016/j.jclepro.2010.11.011.

Changani S.D., Belmar-Beiny M.T., Fryer P.J. 1997. Engineering and chemical factors associated with fouling and cleaning in milk processing. *Exp. Therm Fluid Sci.*, 14, 392–406. DOI: 10.1016/S0894-1777(96)00141-0.

Diakun J., Mierzejewska S., Kukiełka K., 2012. The regression equation of energy requirement in the process of cleaning the pipeline by CIP method. *Polish Journal of Food Engineering,* 1/4(1), 5–8.

Eide, M.H., Homleid, J.P., Mattsson, B., 2003. Life cycle assessment (LCA) of cleaningin-place processes in dairies. *LWT Food Sci. Technol.,* 36, 303-314. DOI: 10.1016/S0023-6438(02)00211-6.

Fryer P.J, Christian G.K., Liu W., 2006. How hygiene happens: physics and chemistry of cleaning. *Int. J. Dairy Technol.,* 59, 76–84. DOI: 10.1111/j.1471-0307.2006.00249.x.

Goode K.R., Asteriadou K., Fryer P.J., Picksley M., Robbins P.T., 2010. Characterizing the cleaning mechanisms of yeast and the implications for Cleaning In Place (CIP). *Food Bioprod. Process.,* 88, 365–374. DOI: 10.1016/j.fbp.2010.08.005.

Jude B., Lemaire E. 2014. Optimising clean-in-place processes in food and beverage operations: Part 1. *Process Control Systems*. Available at: http://www.processonline.com.au/articles/69571.

Kowalczyk R., Karp K., 2005. Energy consumption at sewage treatment in selected plant of dairy industry. *Problemy Inżynierii Rolniczej*, 4, 79–88.

Krzemińska D., Neczaj E., Parkitna K., 2013. Zastosowanie reakcji Fentona do wspomagania biologicznego oczyszczania ścieków z przemysłu mleczarskiego. *Annual Set The Environment Protection,* 15, 2381–2397.

Kukiełka, L., 2002. *Basics of engineering research*. PWN, Warszawa, 174–208.

Marchini D., Rinaldi M., Montanari R., Bottani E., Solari F., 2014. Performance analysis of the water supply system of a dairy company by means of an advanced simulation tool. *Int. J. Food Eng.*, 10, 557–571. DOI: 10.1515/ijfe-2013-0067.

Marchini D., Rinaldi M., Montanari R., Bottani E., Solari F., 2015. Temperature analysis of the water supply system of a dairy company by means of a simulation model. *Int. J. Food Eng.*, 11, 731–745. DOI: 10.1515/ijfe-2015-0065.

Neryng A., Wojdalski J., Budny J., Krasowski E., 1990. *Energy and water in agro-food industry*. WNT, Warsaw, 103–106, 189–194.

Pawełas A., 2010. Energy effectiveness on the example of the brewery. *Agro Industry*, 3-4, 44-47.

Piepiórka J., 2012. Comparison of evaluation methods degree of cleaning surface production in the CIP system. *Polish Journal of Food Engineering,* 2/4(2), 23–26. Available at: http://ips.wm.tu.koszalin.pl/doc/ 2012/2.2012/5_art_piepiórka-stepuk.pdf.

Piepiórka-Stepuk J., Diakun J., Mierzejewska S., 2016. Poly-optimization of cleaning conditions for pipe systems J. and plate heat exchangers contaminated with hot milk using the Cleaning In Place method. *J. Cleaner Prod.,* 112, 946-952. DOI: 10.1016/j.jclepro.2015.09.018.

Rad S.J., Lewis M.J., 2014. Water utilisation, energy utilisation and waste water management in the dairy industry: A review. *Int. J. Dairy Technol.*, 67, 1-20. DOI: 10.1111/1471-0307.12096.

Ramirez C.A., Patel M., Blok K. 2006. From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. *Energy*, 31, 1984-2004. DOI: 10.1016/j.energy.2005.10.014.

Steinhoff-Wrześniewska A., Rajmund A., Godzwon J., 2013. Water consumption in selected branches of food industry. *Inżynieria Ekologiczna*, 32, 164–171.

Williams P.J., Anderson P.A., 2006. Operational cost savings in dairy plant water usage. *Int. J. Dairy Technol.*, 59, 147–154. DOI: 10.1111/j.1471-0307.2006.00256.x.

Wojdalski J., Dróżdż B., 2012. Energy efficiency of food processing plants key issues and definitions. *Polish Journal of Food Engineering,* 3/4(3), 37–49.

Wojdalski J., Dróżdż B., Piechocki J., Gaworski M., Zander Z., Marjanowski J., 2013. Determinants of water consumption in the dairy industry. *Pol. J. Chem. Technol.,* 15, 61-72. DOI: 10.2478/pjct-2013-0025.

Wojdalski J., Kaleta A., Dróżdż B., Chojnacka A., 2012. Factors influencing the energy efficiency in dairy processing plants. *TEKA Commission of Motorization and Energetic in Agriculture,* 12(1), 307–313.