

# Minimising the environmental footprint of industrial-scaled cleaning processes by optimisation of a novel clean-in-place system protocol

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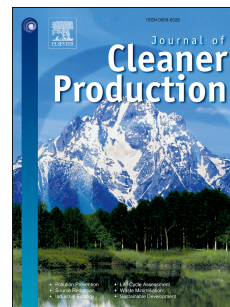
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# Accepted Manuscript

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Ibrahim Palabiyik, Mustafa Tahsin Yilmaz, Peter J. Fryer, Phillip T. Robbins, Ömer S. Toker



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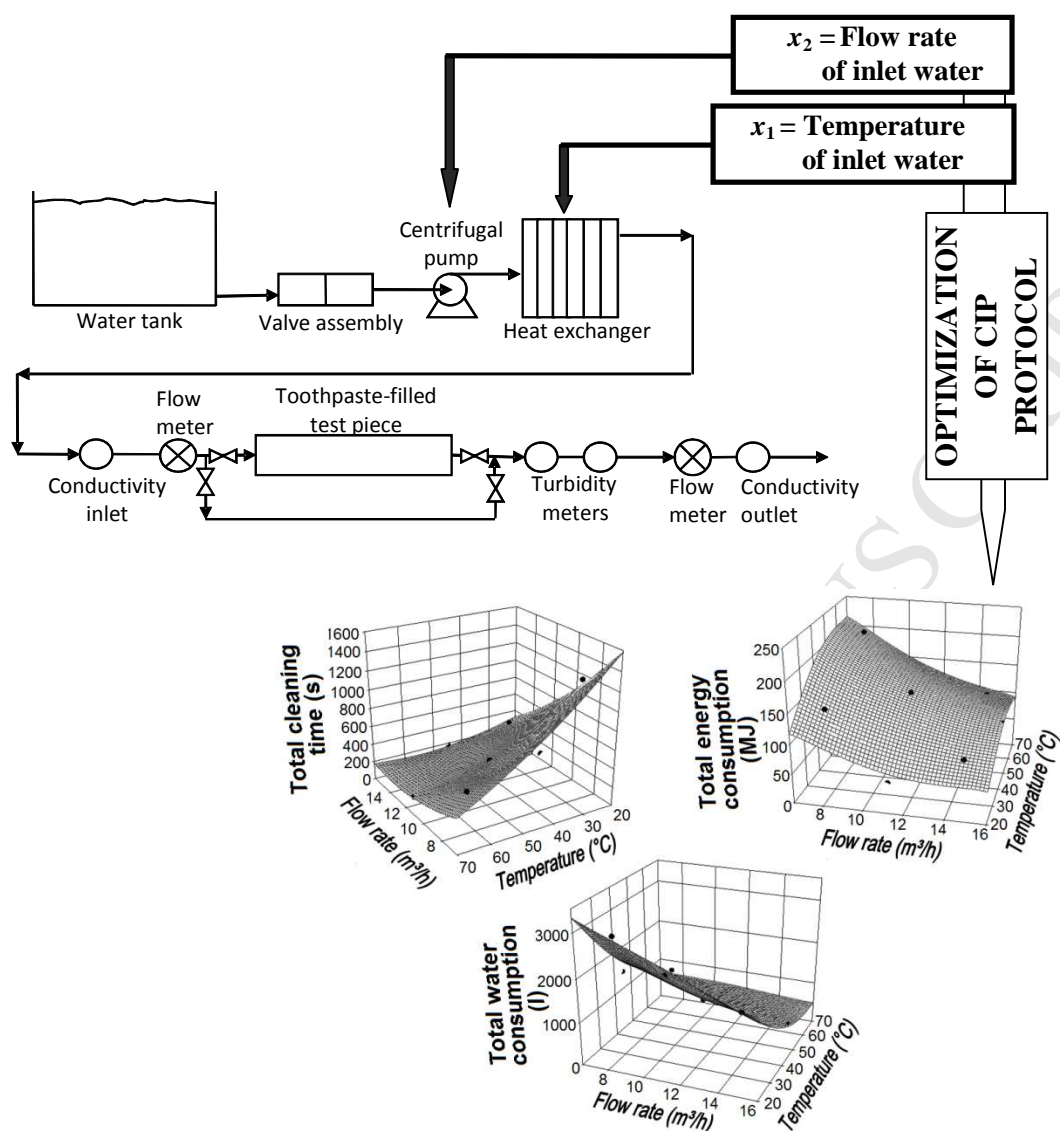


Fig. 1. Schematic representation of the pilot plant for optimization of cleaning-in-place protocol (CIP).

# 1 **Minimising the environmental footprint of industrial- scaled cleaning** 2 **processes by optimisation of a novel clean-in-place system protocol**

3  
4 **Running title:** Clean-in-place optimisation in food plants

5  
6 Ibrahim Palabiyik <sup>a</sup>, Mustafa Tahsin Yilmaz <sup>b,\*</sup>, Peter J. Fryer <sup>c</sup>, Phillip T. Robbins <sup>c</sup>, Ömer S. Toker <sup>b</sup>

7  
8 <sup>a</sup>*Namik Kemal University, Department of Food Engineering, 59000, Tekirdag, Turkey*

9 <sup>b</sup>*Yıldız Technical University, Chemical and Metallurgical Engineering Faculty, Food Engineering Department,*  
10 *34210, İstanbul, Turkey*

11 <sup>c</sup>*University of Birmingham, Department of Chemical Engineering, Edgbaston, Birmingham B15 2TT, UK*  
12  
13

## 14 **ABSTRACT**

15 Cleaning of food fouling deposits in processing equipment is costly and time consuming.  
16 Fouling deposits form as a result of adhesion of species to the surface and cohesion between  
17 elements of the material. Cleaning can result from either or both adhesive and cohesive  
18 failure. In this study, the aim was to investigate the removal kinetics of an adhesive material  
19 and to design a novel cleaning in place (CIP) protocol for these kinds of materials at industrial  
20 scale to reduce environmental impact of cleaning processes. It was detected that different  
21 variables controlled the cleaning process in removal of adhesive deposit. Temperature was not  
22 found as a significant variable in the initial stage of cleaning. Velocity of cleaning water  
23 controlled the cleaning at this stage when top layers of the deposit were removed by fluid  
24 mechanical removal due to breakdown of weak cohesive interaction. In the later cleaning  
25 stage, both velocity and temperature significantly contributed to cleaning, which suggested  
26 that both hydrodynamic forces and rheological changes are needed to overcome adhesion  
27 forces between the deposit and surface. Hence, a novel “two step CIP protocol” was proposed  
28 due to existence of different mechanisms in cleaning. When compared with conventional one  
29 step CIP protocols currently used in the processing plants, the proposed CIP protocol reduced  
30 the energy consumption by 40 % without decreasing the cleaning efficiency.

31 **Keywords:** Cleaning in place, optimisation, adhesive material, pilot scale experiments,  
32 response surface methodology

\* Corresponding author. Tel.: +90 212 383 4575/fax.: +90 212 383 4571.  
E-mail address: mtyilmaz@yildiz.edu.tr (M.T. Yilmaz).

## 33 1. Introduction

34 Fouling, the unwanted build-up of deposits on a surface is a significant problem in many  
35 different industries. As a result, regular cleaning of production equipment is needed. Fouled  
36 deposits result in pressure drop and reduce the efficiency of processing equipment, increasing  
37 operating costs. Moreover, fouling may compromise product quality by cross contamination,  
38 which reveals the necessity for effective cleaning procedures. In many industries, cleaning is  
39 performed by a cleaning-in-place (CIP) procedure. This involves the circulation of hot  
40 cleaning fluids through a closed system of pipes and heat exchangers without dismantling any  
41 component from production line.

42 For effective cleaning, a considerable amount of water and energy is consumed at  
43 industrial scale applications, which requires process optimisation. Especially, water is an  
44 important material since it provides material flow (Koroneos et al., 2005). However, the  
45 conditions used in CIP are far from optimal. This is both because cleaning is still poorly  
46 understood (Fryer and Asteriadou, 2009) and significant brand damage may occur if  
47 contaminated product reaches the market. Cleaning has considerable economic and  
48 environmental impact (Jeurnink, and Brinkman, 1994) as it consumes substantial resources  
49 (Cole, 2011):

- 50 • high water and possible cleaning chemical usage
- 51 • energy usage to heat, pump the water and operate equipment during cleaning

52 Increasing fuel costs and legislative pressures towards zero emission processes make  
53 optimisation of cleaning protocols crucial. Process optimisation makes reduction in water and  
54 energy consumption possible at industrial scale, which would result in reduced economic and  
55 environmental costs such as cleaning utilization of cleaning agents (Kirby et al., 2003;  
56 Pettigrew et al., 2015). Therefore; one of the most important aims of cleaning research should  
57 be to minimise cleaning costs and the amount of effluent released during cleaning.

58 There are two steps to achieve this:

59 i) to understand and explore the mechanisms of cleaning and identify how process  
60 variables affect cleaning,

61 ii) to optimise the process in terms of water, energy used and time spent during cleaning.

62 Processing of fluid foods at an industrial scale is consisted of a complex series of  
63 sequential and simultaneous batch/continuous processes. This is why proper analysis of these  
64 processes chains in challenging step in terms of monitoring and optimising process efficiency  
65 (Pettigrew et al., 2015). In this respect, any cleaning process must overcome both the (i)  
66 cohesive forces that bind elements of deposit together, as well as (ii) adhesion forces between  
67 the deposit and surface. Many food and personal care processes involve the removal of  
68 product (such as pastes and creams) that forms layers thicker than 1 cm on the surfaces of  
69 tanks and vessels and can completely fill pipework.

70 In previous work (Palabiyik et al., 2014), a number of kinetic processes were observed in  
71 the cleaning of a viscoelastic material (toothpaste) from a fully filled straight pipe. Three  
72 stages were identified; (i) a short “core removal stage” of product recovery, before water  
73 breaks through the filled pipe, (ii) “a film removal stage” when there is a continuous wavy  
74 annular film of material on the wall, and (iii) “a patch removal stage” in which the material is  
75 present as patches on the wall. These stages were found in the cleaning of other yield stress  
76 materials, such as hand cream and ketchup. Core removal displaced about 50 % of the  
77 material in the tube. In the film removal stage, where cleaning disrupted the cohesive forces  
78 between deposit elements, ca. 95 wt% of the remaining deposit film was removed, largely as  
79 chunks of material. In the patch removal stage, adhesive forces between deposit elements and  
80 surface governed cleaning. Removal of deposit was slow; around half of the total cleaning  
81 time was spent in this stage to remove the remaining 5 wt% of the deposit.

82 Toothpaste was used as a model deposit; little work has been done on this type of fluids,

83 as previous studies have generally focused on cleaning of deposits formed after heat treatment  
84 (Christian and Fryer, 2006; Liu et al., 2007). Also, cleaning is anticipated to depend on the  
85 material rheology for this kind of deposits (Fryer and Asteriadou, 2009). Results may well be  
86 appropriate for the cleaning of a wide range of yield stress materials in the food and personal  
87 care industries, where products are commonly of complex rheology. Existence of these  
88 different stages suggests that cleaning might be optimised by applying different cleaning  
89 conditions in each region. General practice in CIP is to circulate hot water rapidly throughout  
90 the process; however, this may not be the best practice.

91 It is important to carry out experiments at an appropriate scale – since, for cleaning, scale-  
92 up rules are not known (Fryer and Asteriadou, 2009). Response Surface methodology (RSM)  
93 is a suitable method to use as it can reveal general trends from the minimum number of  
94 experiments. It is a very effective tool in the statistical modelling and optimisation studies  
95 (Baş and Boyaci, 2007; Velioglu et al., 2010). Many response surface problems involve the  
96 analysis of several responses. To perform a simultaneous consideration of multiple responses,  
97 an appropriate response surface model should be built for each response at the first step.  
98 Following this, a set of operating conditions that optimises the response should be estimated  
99 (Montgomery, 2001). In this respect, some of the variables are aimed to be maximised and  
100 some to be minimised. However, a competition occurs between these responses in many  
101 cases; namely, improving one response may lead another response to deteriorate. Several  
102 approaches have been developed to overcome this. Constrained optimisation may be used, or  
103 different response surfaces superimposed to identify optima. Alternatively, a desirability  
104 function, which combines all the responses into one measurement, could be used. This has  
105 three advantages: (i) different scaled responses can be compared, (ii) different responses can  
106 be simply and quickly transformed to a single measurement, and (iii) it is possible to  
107 simultaneously use qualitative and quantitative responses (Harrington, 1965; Derringer and

108 Suich, 1980).

109 The main aim of this work was to find an CIP protocol with a lower environmental  
110 footprint compared to conventional CIP protocols in food and chemical processing plants.  
111 Some previous works suggest advantages of applying different CIP procedures such as  
112 pulsing cleaning chemicals (Christian and Fryer, 2006) or pulsed flows (Blel et al., 2009).  
113 The following issues are addressed;

- 114 • to determine the degree to which cleaning depends on temperature and velocity;
- 115 • to detect how this dependence changes during cleaning and;
- 116 • to perform CIP optimisation by using the multiple response optimisation (MRO)  
117 technique of response surface methodology.

118

## 119 **2. Materials and methods**

### 120 ***2.1. Materials and pilot plant***

121 Toothpaste was supplied by GSK (Brentford, UK). It is a Herschel–Bulkley fluid with  
122 an apparent yield stress of 92 Pa and is shear thinning according to (based on a model fit):

123

$$124 \quad \sigma = 92 + 0.55(\gamma)^{0.78} \quad (1)$$

125

126 where  $\sigma$  and  $\gamma$  are shear stress (Pa) and shear rate ( $s^{-1}$ ), respectively (Cole et al., 2010).

127 A pilot plant system at industrial scale was used to simulate a CIP set-up to monitor the  
128 cleaning procedure of toothpaste from pipe work. Industrially, cleaning fluid is generally  
129 recirculated or recycled to allow a more efficient use of resource. In this case, water was not  
130 recycled to allow quantification of the amount of water consumed during cleaning. The  
131 experiments were conducted in a pilot plant system previously used in cleaning studies at  
132 University of Birmingham (Cole et al., 2010).



133 A schematic of the pilot plant system is illustrated in Fig. 1. A centrifugal pump  
134 (Variflow centrifugal pump, 3 bar, 5.5 kW) being capable of transferring up to 20 m<sup>3</sup>/h (3.1  
135 m/s) water was used to pump water around the system. The test section used in this work was  
136 0.5 m long pipe with a 0.0477 m ID and 1.6 mm wall thickness. The instrumentation used  
137 were:

138 • in-line inductive conductivity probes (conductivity and temperature, LMIT 08: Ecolab  
139 Ltd.), flow meters (Promag 51P, Endress-Hauser, from Ecolab Ltd.) at the inlet and outlet of  
140 the system

141 • two turbidity meters at outlet; Kemtrak TC007, (Kemtrak ab) and Optek TF16 (Optek-  
142 Danulat GmbH).

143 In this study, the Optek turbidity meter was used to monitor cleaning process over time  
144 since it was calibrated to provide greater detail at the lower end of the cleaning experiment. A  
145 reading of '3 ppm' on the Optek turbidity meter was selected as the end-point of cleaning for  
146 proper comparison. In the early stages of cleaning the sensor saturated, but at the 3 ppm mark,  
147 visual examination showed the pipe to be completely clean or with only a few tiny islands of  
148 deposit, with <0.1 % of the starting weight remaining. The same cleaning procedure was  
149 applied as in previous work (Cole et al., 2010).

150

## 151 ***2.2. Determination of cleaning times, energy and water consumption during cleaning***

152 In the previous study (Palabiyik et al., 2014), a short pulse of cold and fast water was  
153 found as the best core removal condition. In the present study, water at 20 °C and 16 m<sup>3</sup>/h (2.5  
154 m/s) was used in the initial 2 s to remove the core of the material from the fully filled  
155 pipework. It was then important to identify when patch removal began. Visual observation  
156 and the online turbidity meter were compared. The glass pipe after the test section was used to  
157 follow the process, and the point where particles of removed material could no longer be seen

158 (the end of film removal) was usually close to the point where the turbidity meter generally  
 159 started to be unsaturated. For simplicity, the flow was divided into two regions; Region 1 for  
 160 which the sensor saturated, and Region 2 for which it did not saturate.

161 Typical cleaning behaviour and cleaning regions are shown in Fig. 2. Data shows the  
 162 response of the turbidity meter at 70 °C and 11.2 m<sup>3</sup>/h (1.75 m/s) water flow. The cleaning  
 163 rate was initially very high, and the turbidity meter was saturated up to 125 s, the duration of  
 164 Region 1. Then, the response decreased exponentially until the end of cleaning. This stage  
 165 was defined as Region 2 and lasted 90 s. For each cleaning stage, water and energy  
 166 consumption were calculated using:

$$167 \quad V = Qt / 3600 \quad (2)$$

168 where  $V$  (m<sup>3</sup>) was volume of the water used during cleaning,  $Q$  (m<sup>3</sup>/h) was the volumetric  
 169 flow rate and  $t$  (s) was time for each region. Energy consumption was calculated by addition  
 170 of hydraulic energy to drive the pump and thermal energy to heat the cleaning water:

$$172 \quad E = \frac{V\rho gh}{\varepsilon} + V\rho c_p \Delta T \quad (3)$$

173  
 174 where  $E$  was energy consumed in megajoule (MJ),  $\rho$  (kg/m<sup>3</sup>) the density of water,  $g$  (9.81  
 175 m/s<sup>2</sup>) the acceleration due to gravity,  $h$  (m) was the friction head loss component of the  
 176 system,  $\varepsilon$  was pump efficiency,  $c_p$  (4185.5 J/kgK) was heat capacity of water and  $\Delta T$  (K) was  
 177 temperature difference (temperature of cleaning water – datum temperature).  $\varepsilon$  was found  
 178 from the pump performance chart as 0.64.  $h$  was calculated as 30 m by finding the maximum  
 179 rate of flow rate of fluid that could be pumped in the pilot plant. Datum temperature was the  
 180 average ambient temperature (17 °C), and 20 °C was selected for the minimum temperature  
 181 for experiments. Pumping energy ranged between 0.3 % and 5 % of the total energy  
 182 consumption in cleaning experiments.

183

184 **2.3. Experimental design and statistical analysis**

185 In the response modelling, multiple linear regression analysis was used and the following  
 186 second-order polynomial equation of function  $x_i$  was fitted for each factor assessed at each  
 187 experimental point.

$$188 \quad \hat{y} - E = \beta_0 + \sum_{i=1}^2 \beta_i x_i + \sum_{i=1}^2 \beta_{ii} x_i^2 + \sum_{\substack{i=1 \\ i < j}}^2 \sum_{j=i+1}^2 \beta_{ij} x_i x_j, \quad (4)$$

189 where  $\hat{y}$  was the estimated response;  $\beta_0$  was the average value of the response at the centre  
 190 point of the design,  $\beta_1$ ,  $\beta_2$ ,  $\beta_{12}$ ,  $\beta_{11}$  and  $\beta_{22}$  were linear, interaction and quadratic terms,  
 191 respectively and  $E$  was the statistical error term.

192 Models were built to describe the effect of independent variables (cleaning water  
 193 temperature and flow rate) on the cleaning time, energy and water consumption for both film  
 194 removal (Region 1), patch removal (Region 2) and the combined total cleaning stages (the 1<sup>st</sup>  
 195 + 2<sup>nd</sup> regions). A 2-factor-5-level Central Composite Rotatable Design (CCRD) with two  
 196 replicates at the centre point was used. The two factors, levels and experimental design in  
 197 terms of coded and uncoded (actual values) can be seen in Table 1. The CCRD is an optimal  
 198 design that allows calculation of a model, with a minimum number of experiments. It consists  
 199 of  $2k$  factorial points (coded as  $\pm 1$  notation), augmented by  $2k$  axial points  $(\pm\alpha, 0, 0, \dots, 0)$ ,  
 200  $(0, \pm\alpha, 0, \dots, 0)$ ,  $(0, 0, \pm\alpha, \dots, 0), \dots, (0, 0, 0, \dots, \pm\alpha)$  located at a specified distance  $\alpha$  from the centre  
 201 in each direction on each axis defined by the coded factor levels.  $n_0$  is each centre point  
 202  $(0, 0, \dots, 0)$ .  $k$  is the number of factors. The relationship between coded and actual values of  
 203 variables was calculated using:

204

$$205 \quad x_i = \frac{z_i - 0.5(z_{i,\max} + z_{i,\min})}{0.5(z_{i,\max} - z_{i,\min})} \quad (5)$$

206  
207 where  $z$  was the actual variable, the subscripts min and max referred to the minimum (27 °C  
208 and 7.86 m<sup>3</sup>/h (1.2 m/s), respectively) and maximum values (63 °C and 14.54 m<sup>3</sup>/h (2.3 m/s),  
209 respectively) and  $x$  was the coded variable. In this study, rotatability was selected; the design  
210 is rotatable if the variance of the response is constant for all variables at a given distance from  
211 the design centre. The CCD is rotatable if:

$$212 \quad \alpha = \sqrt[k]{2^k} \quad (6)$$

213  
214  
215 The best fitting models were determined using multiple linear regressions with backward  
216 elimination regression (BER) where insignificant factors and interactions were removed from  
217 the models and only variables significant at  $P < 0.01$ ,  $P < 0.05$  and  $P < 0.1$  levels were selected  
218 for the model.

#### 219 220 **2.4. Multiple response optimisation (MRO)**

221 The operating conditions,  $x$  providing the “most desirable” response values can be found  
222 by multiple response optimisation. Different desirability functions  $d_i(Y_i)$  can be used  
223 depending on whether a particular response  $Y_i$  is to be maximized and minimised (Derringer  
224 and Suich, 1980).

225 Let  $L_i$ ,  $U_i$  and  $T_i$  be the lower, upper and target values, respectively, desired for response  
226  $Y_i$ . If a response is to be maximized, then its individual desirability function is with the  
227 exponent  $s$  that determines how significant it is to hit the target value. For  $s = 1$ , the  
228 desirability function increases linearly towards  $T_i$  which indicates a large adequate value for  
229 the response; for  $s < 1$ , the function is convex, and for  $s > 1$ , the function is concave (Eren and  
230 Kaymak-Ertekin, 2007):

231

$$d_i(\hat{y}_i) = \begin{cases} 0 & \hat{y}_i(x) < L_i \\ \frac{\hat{y}_i(x) - L_i}{T_i - L_i} & L_i \leq \hat{y}_i(x) \leq T_i \\ 1 & \hat{y}_i(x) > T_i \end{cases} \quad (7)$$

233

234 If a response is to be minimised, then its individual desirability function is with  $T_i$ , which  
235 indicates a small adequate value for the response:

$$d_i(\hat{y}_i) = \begin{cases} 1 & \hat{y}_i(x) < T_i \\ \frac{\hat{y}_i(x) - U_i}{T_i - U_i} & T_i \leq \hat{y}_i(x) \leq U_i \\ 0 & \hat{y}_i(x) > U_i \end{cases} \quad (8)$$

237

238 Having computed for each response variable, desirability values were combined into a  
239 single desirability index,  $D$ . For this purpose, each response was transformed in a  
240 dimensionless function, the partial desirability function,  $d_i$ , which reflects the desirable ranges  
241 for each response. The desirable ranges varies from zero to one (least to most desirable). The  
242 global desirability function  $D$  is the weighted geometric mean of  $n$  individual desirability  
243 functions (all transformed responses) [Eq. (9)]. The simultaneous objective function is a  
244 geometric mean of all transformed responses (Lewis et al., 1999; Myers and  
245 Montgomery, 1995):

246

$$D = \left( d_1^{p_1} \cdot d_2^{p_2} \cdot d_3^{p_3} \cdot \dots \cdot d_n^{p_n} \right)^{1/\sum p_i} \quad (9)$$

$$= \prod_{i=1}^n d_i^{p_i / \sum_{i=1}^n p_i}$$

248 where  $p_i$  was the weighting of the  $i$ th term, and was normalized in order that  $\sum_{i=1}^n p_i = 1$ . By

249 weighting of partial desirability functions, it is possible to enable the optimisation process to  
250 take the relative importance of each response into consideration. Allowing the examination of  
251 the form of the desirability function, it is permitted to find the region where the function is  
252 close to 1 and to determine the compromise optimum conditions.

253 In the present study, multiple response optimisation were separately conducted for each  
254 stage, with parameters;

- 255 • *Region 1* : “film removal ”; first cleaning time - FCT; first energy consumption -  
256 FEC; first water consumption - FWC,
- 257 • *Region 2*: “patch removal stage”; second cleaning time - SCT; second energy  
258 consumption - SEC; second water consumption- SWC ) and
- 259 • *Total cleaning*: ; total cleaning time - TCT; total energy consumption -TEC; total  
260 water consumption - TWC.

261 In each stage the aim was to minimise cleaning time, energy and water usage. The same  
262 importance was applied to each response during the optimisation analysis. The modelling  
263 procedure and optimisation methodology by RSM is diagrammed in Fig. 3. The  
264 computational work was performed using a statistical package, Design-Expert version 7.0  
265 (Stat-Ease Inc., Minneapolis, USA).

266

### 267 **3. Results and discussion**

#### 268 ***3.1. Interpretation of the RSM model fit***

269 Table 1 shows the coded and actual levels of the experimental factors (independent  
270 variables). The experiments were run in a random order to minimise the effect of  
271 uncontrollable variables. Tables 2, 3 and 4 show the ANOVA results used to evaluate the  
272 significance of the constructed quadratic models. Model terms were used after the  
273 insignificant ones were eliminated, and other statistical parameters were obtained using

274 backward elimination regression (BER) procedure. The fits for the models were significant  
275 ( $P>0.05$ ), indicating that the fitted models could describe the variation of the data.

276 Residual analysis,  $R^2$  (coefficient of determination),  $\text{adj-}R^2$  (adjusted  $R^2$ ),  $\text{pred-}R^2$   
277 (predicted  $R^2$ ) and adequate precision (adeq-precision) values were used to check the  
278 adequacy of the models (Tables 2-4). The  $R^2$  values generally ranged between 0.790 and  
279 0.988, indicating that the models generated were adequate. An adequate precision value  
280 greater than 4 is desirable. In practice, values between 9.24 and 24.0 were found (Tables 2-4)  
281 which indicated that these models could be used to navigate the design space. Results in  
282 Tables 2-4 show;

283 • ( $R^2$ ) values for time, energy and water consumption were 0.921, 0.912 and 0.936 when  
284 variables (temperature and flow rate) were fitted to data for the total cleaning process.

285 • However, when variables were fitted to Regions 1 and 2 separately,  $R^2$  values for time,  
286 energy and water consumption increased (to 0.988, 0.906 and 0.975, respectively for Region  
287 2).

288 The model thus gave a better description of cleaning when Regions 1 and 2 were  
289 considered separately. This suggested that Regions 1 and 2 had different cleaning kinetics,  
290 and that both have to be considered in an optimum CIP protocol.

## 292 ***3.2. The effect of temperature and flow rate***

### 293 ***3.2.1. Cleaning times***

294 The effects of temperature and flow rate values on the cleaning times in Region 1 are  
295 presented in Tables 2-4. Results clearly revealed that linear effects of the temperature were  
296 significant ( $P<0.01$ ) in all stages (Tables 2-4). Fig. 4 illustrates these effects as response  
297 surfaces. Fig. 4-a shows that at high flow rates ( $16\text{ m}^3/\text{h}$ - $2.5\text{ m/s}$ ), increasing the temperature  
298 has little effect on cleaning times in Region 1. In this case, breakage of cohesive bonds in the

299 deposit controls cleaning; data suggests that beyond some flow velocity these bonds are weak  
 300 enough to be broken by flow, so further increase in temperature has little effect. However,  
 301 temperature had a considerable impact in the cleaning time in Region 2 in Fig. 4-b. At any  
 302 flow rate, increasing temperature decreased the cleaning time. These results implied that the  
 303 adhesive bonds that must be broken to remove the final layers of deposit are temperature  
 304 sensitive. This is in agreement with the work of Akhtar et al. (2010) who found that toothpaste  
 305 showed higher adhesive than cohesive forces. Whey protein deposits (Liu et al., 2006) and  
 306 yeast (Goode, 2011) were also found to have this behaviour. For all of these deposits, cleaning  
 307 occurred through removal of chunks initially, and the last stages of removal was the limiting  
 308 step (Goode, 2011; Bird and Fryer, 1991).

309 For the effect of flow rate, cleaning times were significantly ( $p < 0.01$ ) influenced by flow  
 310 velocity in all regimes (Tables 2-3). From the Fig. 4 (a, b and c), the cleaning times (FCT,  
 311 SCT and TCT) can be observed to decrease with flow rate at each stage.  
 312 These results again showed different kinetics in the two regions, therefore different cleaning  
 313 protocols should used in each stage for optimisation, this will be discussed in section 3.3.  
 314 To improve the accuracy of the regression model equations, their insignificant ( $p > 0.1$ ) factors  
 315 and interactions were removed from the models using BER. They were generated to predict  
 316 effects of the processing variables in Fig. 4 and calculated:

317

$$318 \hat{Y}_{(\text{first cleaning time, } FCT)} = 1611 - 19.62(T) - 100.2(FR) + 1.297(T)(FR) \quad (10)$$

$$319 \hat{Y}_{(\text{second cleaning time, } SCT)} = 2.404 - 35.57(T) - 191.6(FR) + 1.052(T)(FR) \quad (11)$$

$$320 \quad \quad \quad + 0.17(T)^2 + 4.85(FR)^2$$

$$321 \hat{Y}_{(\text{total cleaning time, } TCT)} = 3148 - 39.75(T) - 183.3(FR) + 2.349(T)(FR) \quad (12)$$

322

323 where  $T$  ( $^{\circ}\text{C}$ ) was the temperature and  $FR$  ( $\text{m}^3/\text{h}$ ) was the flow rate.



324

325 **3.2.2. Energy consumption**

326 Tables 2-4 show the effects of temperature and flow rate on energy consumption in  
 327 cleaning. Significant ( $p < 0.01$ ) linear effects of temperature were observed for energy  
 328 consumption in Region 1. Energy usage in this stage increased as the temperature of the  
 329 cleaning water increased. As temperature did not help cleaning in this stage, as noted above,  
 330 increased temperature of the cleaning water caused energy waste. However, in Region 2, an  
 331 increase in the temperature did not have a clear effect on the energy consumption (SEC)  
 332 (Table 3 and Fig 4-e), which indicated the complexity of the cleaning process in Region 2.  
 333 Figure 4-e shows that raising temperature to 50 °C increased the energy usage, and a further  
 334 increase above 50 °C reduced energy usage especially at the highest flow rate. Hence, results  
 335 implied that there was a threshold temperature value above which adhesive bonds of the  
 336 deposit were weakened so that they could be easily removed. Thus, energy usage was reduced  
 337 by improved cleaning efficiency at high temperatures.

338 FEC, SEC and TEC were ( $p < 0.01$ ) influenced by flow rate (Tables 2-4). Fig. 4 (d, e and  
 339 f), showed that these values decreased with flow rate at each stage, indicating that energy  
 340 waste can be decreased with increasing flow rates. Again this showed the importance of flow  
 341 rate in the whole cleaning process.

342 The second order regression model equations, after insignificant ( $p > 0.1$ ) factors were  
 343 removed, were as follows:

$$344 \hat{Y}_{(\text{first energy consumption, } FEC)} = 69.41 + 1.406(T) - 5.187(FR) \quad (13)$$

$$345 \hat{Y}_{(\text{second energy consumption, } SEC)} = 129.7 + 3.183(T) - 20.95(FR) - 0.036(T)^2 + 0.727(FR)^2$$

346 (14)

$$347 \hat{Y}_{(\text{total energy consumption, } TEC)} = 60.07 + 7.35(T) - 9.83(FR) - 0.067(T)^2 \quad (15)$$

348 where  $T$  (°C) was the temperature and  $FR$  (m<sup>3</sup>/h) was the flow rate.

349

350 **3.2.3. Water consumption**

351 As can be seen from tables 2-4, linear effects of temperature were found significant  
 352 ( $P < 0.01$ ) on water consumption at all stages. Fig. 4-g showed that water usage in Region 1  
 353 could be slightly reduced by increasing the temperature at the highest flow rate ( $16 \text{ m}^3/\text{h}$ - $2.5$   
 354  $\text{m/s}$ ). Whereas in Region 2, Fig 4-h showed that increased temperature of cleaning water  
 355 decreased the water consumption regardless of the flow rate. This result indicated that  
 356 increasing temperature levels at this region would be advantageous for the environmental  
 357 impact due to less amount of water released during cleaning.

358 FWC, SWC and TWC were significantly ( $p < 0.01$ ;  $0.05$ ) influenced by flow (Tables 2-4).  
 359 From Fig. 4 (g, h and i), it was seen that the water consumption values (FWC, SWC and  
 360 TWC) decreased with flow rate at each stage. The second order regression model equations  
 361 after insignificant ( $p > 0.1$ ) factors and interactions were removed from the models were:

362

$$363 \hat{Y}_{(\text{first water consumption, FWC})} = 1922 - 13.81(T) - 52.96(FR) \quad (16)$$

$$364 \hat{Y}_{(\text{second water consumption, SWC})} = 2944 - 62.98(T) - 41.19(FR) + 0.43(T)^2 \quad (17)$$

$$365 \hat{Y}_{(\text{total water consumption, TWC})} = 5285 - 98.13(T) - 94.14(FR) + 0.666(T)^2 \quad (18)$$

366 where  $T$  ( $^{\circ}\text{C}$ ) was the temperature and  $FR$  ( $\text{m}^3/\text{h}$ ) was the flow rate.

367

368 Similar trends between second cleaning region and total cleaning profile in figures 4-b  
 369 and 4-c, 4-e and 4-f, 4-h and 4-i importantly illustrated that Region 2 was the dominating  
 370 stage which generally comprised 60-70 % of the total cleaning time, and mechanisms in the  
 371 removal of the last patches of deposit were the limiting processes in overall cleaning.

372

373 **3.3. Finding an optimum CIP protocol**

374 In this study, the multiple response optimisation (MRO) technique was separately applied  
375 for stage 1 (FCT, FEC, FWC), stage 2 (SCT, SEC, SWC) and total cleaning stage (TCT, TEC,  
376 TWC). For optimisation, desirability functions of RSM were used to obtain the resultant  
377 optimum operating conditions with the minimisation of the values for each stage (Eq. 9). The  
378 desirability values ( $D$ ) for the minimisation were calculated to be 0.897, 0.998 and 0.910 for  
379 stage 1, stage 2 and total cleaning stages, respectively, indicating that all responses or factors  
380 were inside acceptable desirability ranges. By applying desirability function method, three  
381 solutions were obtained for each optimisation process (minimisation).

382 For the most desirable solutions for the minimisation of each response variable (time,  
383 energy and water consumption) at each removal stage, the following conditions should be  
384 applied:

- 385 • 20 °C and 16 m<sup>3</sup>/h (2.5 m/s) in region 1. At this circumstance, the solution had the  
386 lowest value of FCT (42.6 s), FEC (22.6 MJ) and FWC (727.4 L) values to get the  
387 optimum CIP protocol.
- 388 • 70 °C and 16 m<sup>3</sup>/h (2.5 m/s) in region 2 which induced the lowest value of SCT (39.1  
389 s), SEC (25.2 MJ) and SWC (108.9 L) values according to response surface models.
- 390 • For the conventional CIP system (without applying different conditions throughout the  
391 cleaning process), 70 °C and 16 m<sup>3</sup>/h (2.5 m/s) should be used for the total cleaning.  
392 At this circumstance, the solution had the lowest value of TCT (64.5 s), TEC (89.2  
393 MJ) and TWC (178.2 L) values. This result confirmed the conditions used in the  
394 conventional CIP protocol. As known, current practice in industrial CIP operations is  
395 to use hot and fast water throughout the cleaning process.

396

### 397 ***3.4. Validation of the optimum CIP protocol***

398 In this part, three CIP protocols were tested at the pilot scale pipe work to validate

399 whether the optimum CIP protocol determined by MRO technique would provide savings in  
400 real applications. These were:

401 **i)** cold conventional CIP protocol - 20 °C water at 16 m<sup>3</sup>/h (2.5 m/s) was used for the  
402 overall cleaning. This kind of flow (high-velocity water at ambient temperature) is often used  
403 in the pre-rinse stage of CIP operations. Cold CIP was chosen to figure out the water saving  
404 when the optimum CIP procedure is used instead of cold CIP.

405 **ii)** hot conventional CIP protocol - 70 °C water at 16 m<sup>3</sup>/h (2.5 m/s) was used for the  
406 overall cleaning. Hot high-velocity water is generally applied in the industry. It was selected  
407 to enable comparison of the energy usage between the hot CIP and optimum CIP protocols.

408 **iii)** the novel two-step CIP protocol – water at 20 °C - 16 m<sup>3</sup>/h (2.5 m/s) was used in  
409 region 1 and water at 70 °C - 16 m<sup>3</sup>/h (2.5 m/s) was used in region 2 as determined in section  
410 3.3. The experiment was done by starting cleaning with water flow at 20 °C - 16 m<sup>3</sup>/h (2.5  
411 m/s). When the turbidity meter began to unsaturate, pump was stopped immediately. Then,  
412 water at 70 °C at the flow rate of 16 m<sup>3</sup>/h (2.5 m/s) was pumped to the system until the  
413 turbidity meter reached to 3 ppm.

414 Fig. 5 showed the measurements on the turbidity meter for the three CIP protocols. It  
415 illustrated that

- 416 • comparable cleaning times were obtained in the hot (100 s) and the optimum CIP (126  
417 s) protocols,
- 418 • in the optimum CIP protocol, water at 20 °C was applied up to 73 s at which  
419 unsaturation started. Right after the application of water at 70 °C, turbidity reading  
420 saturated again during the time elapse between 73 and 106 s due to increase in the  
421 removal rate induced by hot water. Then, a very quick region 2 was observed after  
422 106<sup>th</sup> s (20 s), which validated the generated response surface models by showing the  
423 temperature sensitivity of this region,

- 424 • the cold CIP protocol caused ca. 100 % (265 s) increase in cleaning time as compared  
425 to the optimum CIP protocol, mainly due to long cleaning time spent in region 2.

426 Fig. 6 shows the results obtained from the tested CIP protocols in terms of cleaning time  
427 (s), energy (MJ) and water (L) consumption. The hot CIP protocol was observed to result in  
428 great reductions (at least 75 %) in terms of cleaning time and water consumption, as compared  
429 to the cold CIP protocol. This showed the advantage of applying hot and high-velocity water  
430 (2.5 m/s-16 m<sup>3</sup>/h) in conventional CIP procedures. However, the hot CIP protocol caused the  
431 highest energy consumption amongst the tested CIP protocols, i.e. almost quadrupled the  
432 amount of energy consumed in the cold CIP protocol.

433 The optimum CIP protocol notably reduced the amount of waste water and cleaning time  
434 by ca. 50 % and 53 %, respectively, compared to the cold CIP protocol. Moreover, 39 MJ less  
435 energy (ca. 40 %) was consumed in the optimum CIP protocol, compared to the hot CIP  
436 protocol. From the results, it can be deduced that in water starved areas, the hot CIP protocol  
437 should be used in cleaning operations in plants. However, sustainability is increasingly  
438 important and one of the major areas where optimisation is sought is in energy usage.  
439 Therefore, the optimum CIP protocol has a big advantage over conventional CIP protocols as  
440 the results imply that it can substantially decrease the carbon footprint and fuel costs of  
441 cleaning processes in plants where adhesive products are manufactured.

442

#### 443 **4. Conclusion**

444 The increasing need to reduce water consumption and emissions in manufacturing  
445 industries demands the improvement of cleaning operations in the food industry. In this study,  
446 two different cleaning stages were identified by the turbidity meter and visual observations.  
447 Although velocity had considerable effects at both stages (stages 1 and 2), the effect of  
448 temperature was not found influential on the cleaning time and water consumptions in stage 1,

449 especially at high flow rates. Consequently, increase in temperature of cleaning water used in  
450 stage 1 increased the energy consumption. However, in stage 2, both temperature and velocity  
451 significantly contributed to cleaning due to the strong adhesive forces of the deposit and  
452 increase in these variables reduced the energy consumption during cleaning.

453 After determination of the kinetics of the two cleaning stages and how cleaning of the  
454 deposit would depend on temperature and flow rate, a novel two step CIP protocol was  
455 designed using MRO technique. The optimum CIP protocol reduced the amount of waste  
456 water and cleaning time by ca. 50 % and 53 %, respectively, compared to the cold one step  
457 CIP protocol. In addition, the energy consumption was reduced by ca. 40% compared to the  
458 hot one step CIP protocol during cleaning.

459 As a result, this work demonstrated how to evaluate the effect of process conditions on  
460 cleaning of a specific deposit. By this, it is possible to design better CIP protocols, which can  
461 be applied to target any similar industrial process in order to substantially decrease the  
462 environmental footprint of processing plants during cleaning.

463

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551 **Figure captions**552 **Fig. 1.** Schematic representation of the pilot plant.553  
554 **Fig. 2.** Typical cleaning behaviour that showed decreasing dirt particle concentration in  
555 effluent water. It was measured with turbidity meter at ppm level. Turbidity reading was  
556 obtained during the cleaning of toothpaste at 70 °C and 11.2 m<sup>3</sup>/h-1.7 m/s from a pilot scale  
557 straight pipe (0.5 m and 0.0477 m ID).558  
559 **Fig.3.** Steps of modelling and optimisation by CCRD of RSM. 1. time, 1. energy and 1. water  
560 indicate cleaning time, energy and water consumptions at stage 1 which ends when turbidity  
561 meter unsaturates. 2. time, 2. energy and 2. water indicate cleaning time, energy and water  
562 consumptions at stage 2 which starts after turbidity meter become unsaturated. Total time,  
563 total energy and total water indicate cleaning time, energy and water consumptions during the  
564 total cleaning process without considering the individual cleaning stages.565  
566 **Fig.4.** Response surface plots of different cleaning stages influenced by varying temperature  
567 and flow rate values of water applied during cleaning. Effect of temperature and flow rate on  
568 (a) FCT, (b) SCT, (c) TCT, (d) FEC, (e) SEC, (f) TEC, (g) FWC, (h) SWC and (i) TWC  
569 values.570  
571 **Fig. 5.** Readings for dirt particle concentration in effluent water (ppm) obtained during three  
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574 **Fig. 6.** Cleaning time, water and energy consumptions measured at three tested (cold, hot and  
575 optimum) CIP protocols (flow rate was 16 m<sup>3</sup>/h in all systems). In cold CIP protocol (grey),  
576 water was used at 20 °C and in hot CIP protocol (black), water was used at 70 °C during the  
577 whole cleaning (without changing conditions at stage 1 and 2). In optimum CIP procedure  
578 (white), water at 20 °C was used at stage 1 and at 70 °C at stage 2.

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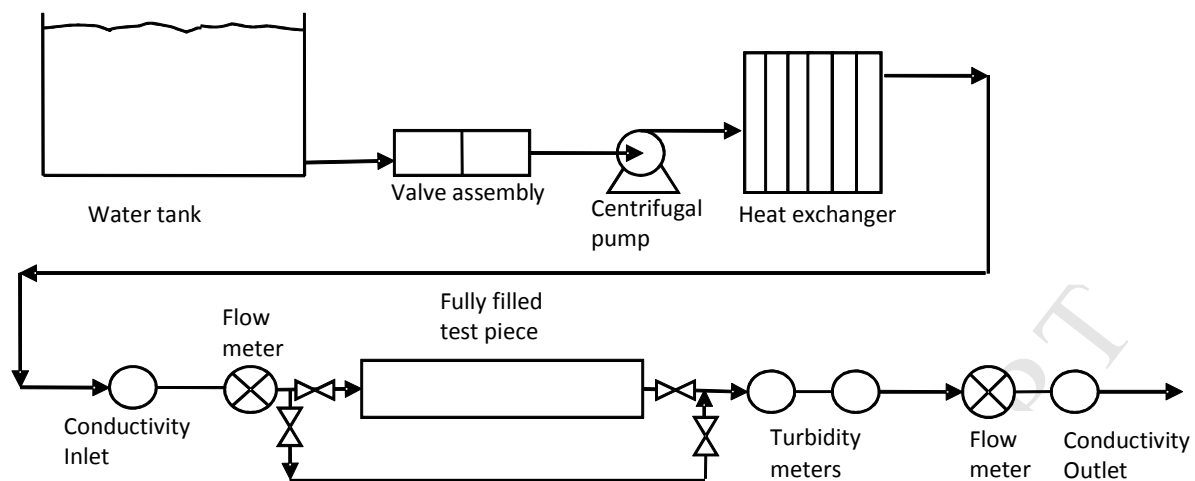
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588 **Fig. 1.** Schematic representation of the industrial scale pilot plant.

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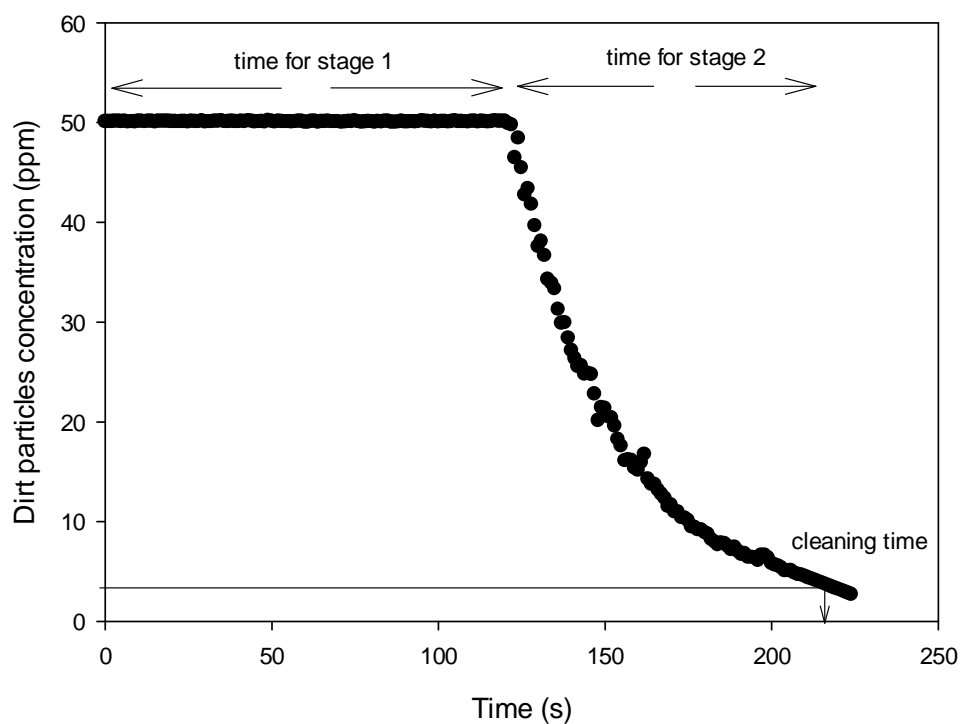
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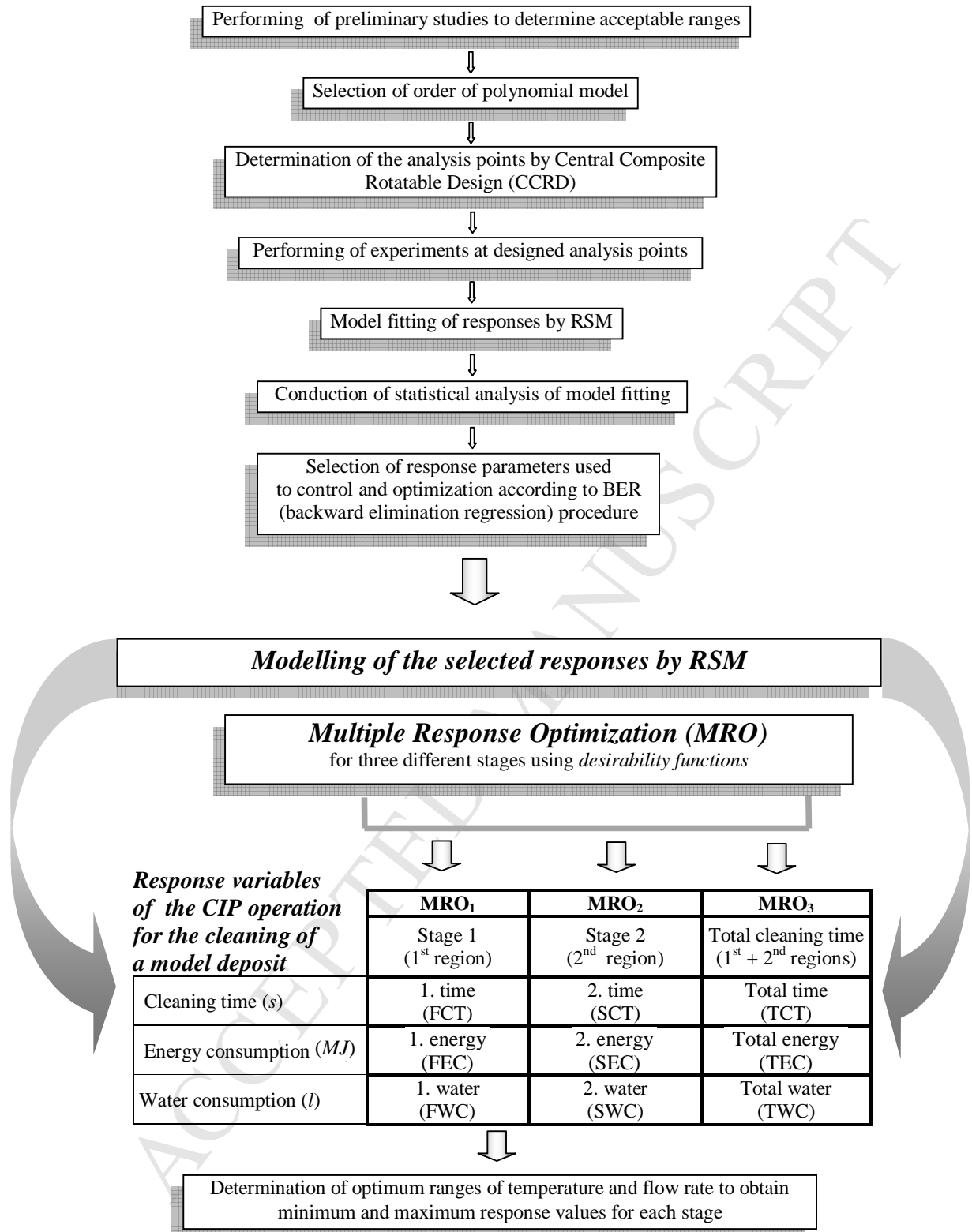
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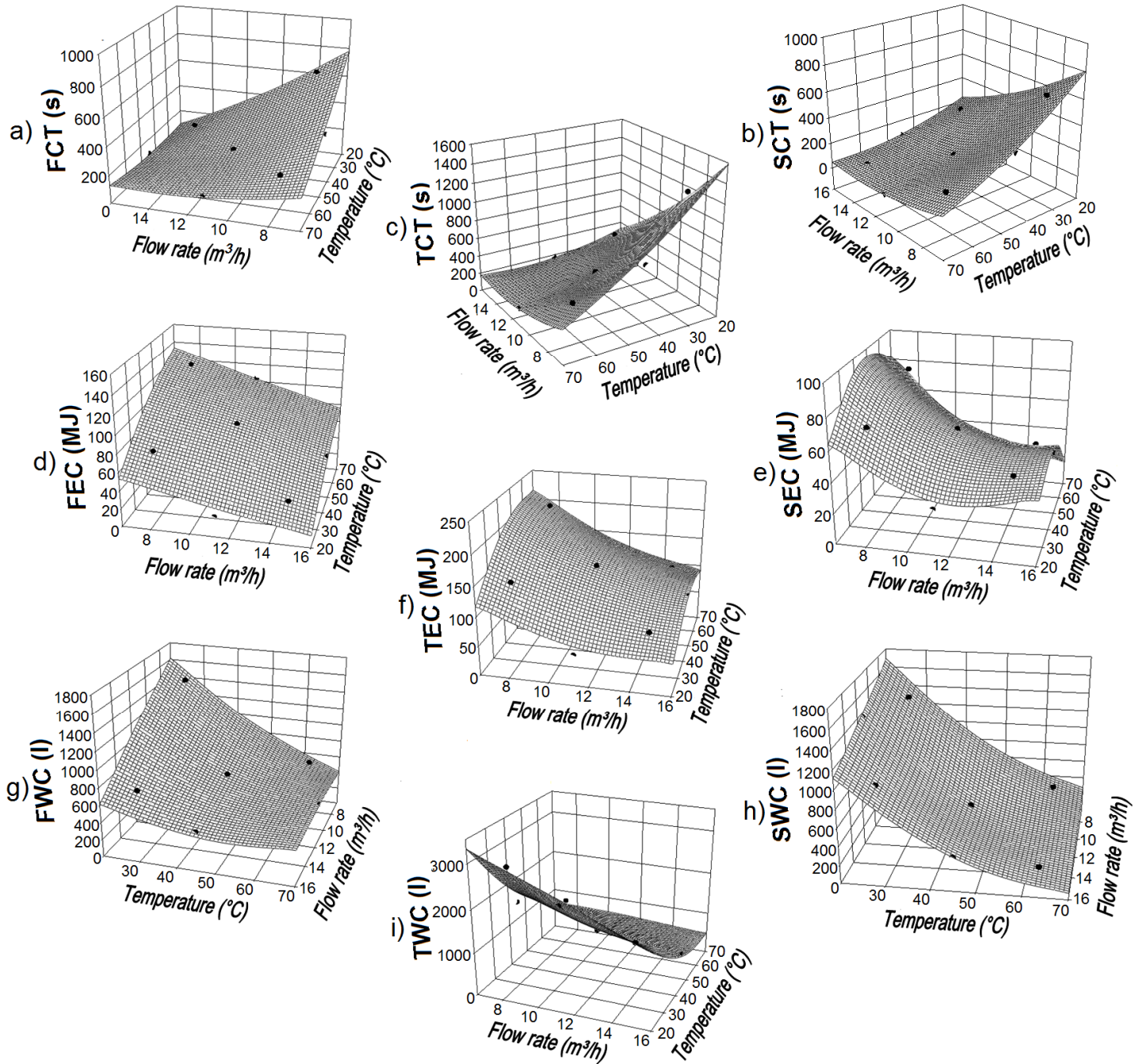
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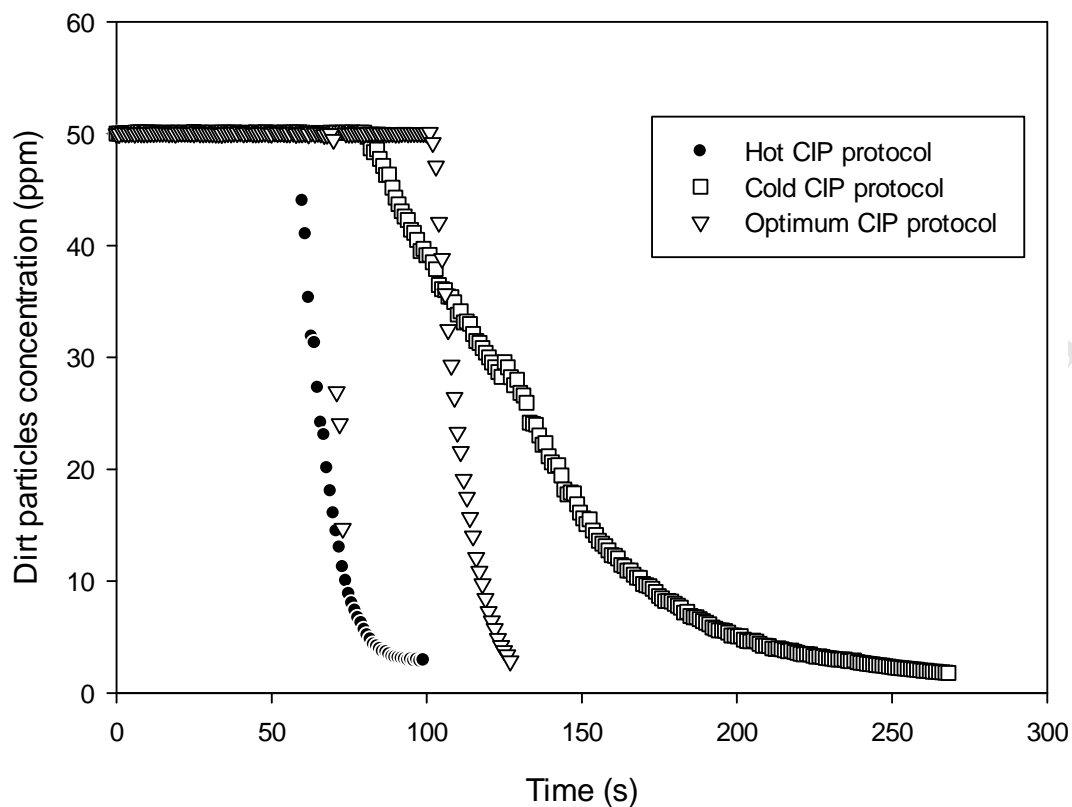
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623 **Fig.3.** Steps of modelling and optimisation by CCRD of RSM. 1. time, 1. energy and 1. water indicate cleaning  
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625 energy and 2. water indicate cleaning time, energy and water consumptions at stage 2 which starts after turbidity  
626 meter unsaturates. Total time, total energy and total water indicate cleaning time, energy and water  
627 consumptions during the total cleaning process without considering the individual cleaning stages.  
628



**Fig.4.** Response surface plots of different cleaning stages influenced by varying temperature and flow rate values of water applied during cleaning. Effect of temperature and flow rate on (a) FCT, (b) SCT, (c) TCT, (d) FEC, (e) SEC, (f) TEC, (g) FWC, (h) SWC and (i) TWC values.



633  
634 **Fig. 5.** Readings for dirt particle concentration in effluent water (ppm) obtained  
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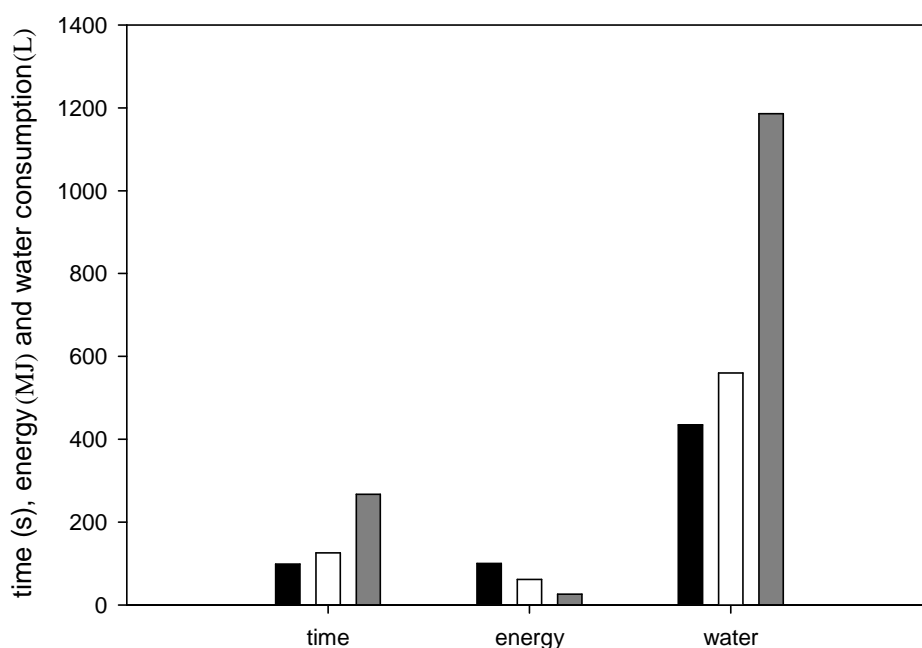
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669 **Table 1**  
 670 Second-order design matrix indicating the levels of coded and actual for two variables

Runs	Coded levels of variables		Actual level of variables <sup>a</sup>	
	Temperature ( $X_1$ )	Flow rate ( $X_2$ )	Temperature (°C)	Flow rate (m <sup>3</sup> /h)
<i>Factorial points</i>				
1	-1	-1	27.0	7.86
2	1	-1	63.0	7.86
3	-1	1	27.0	14.54
4	1	1	63.0	14.54
<i>Axial points</i>				
5	$-α$ (-1.414)	0	19.5	11.20
6	$+α$ (+1.414)	0	70.5	11.20
7	0	$-α$ (-1.414)	45.0	6.48
8	0	$+α$ (+1.414)	45.0	15.92
<i>Center points</i>				
9	0	0	45.0	11.20
10	0	0	45.0	11.20

671 <sup>a</sup>Temperature and flow rate values are those values of the water used during cleaning.  
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701 **Table 2**  
 702 Mean values of first cleaning time (FCT), first energy consumption (FEC) and first water consumption (FWC), the  
 703 significance of the regression models ( $F$  values) and the effects of temperature ( $b_1$ ) and flow rate ( $b_2$ ) on FCT, FEC and  
 704 FWC measured at stage 1

Runs	$I^{st}$ stage					Source of variance	$F$ values and effect of independent variables					
	Independent variables		Dependent variables				FCT		FEC		FWC	
	Temp. ( $^{\circ}C$ )	Flow rate ( $m^3/h$ )	FCT (s)	FEC (MJ)	FWC (L)		DF	$F$	DF	$F$	DF	$F$
<i>Factorial points</i>						Model	3	17.68 <sup>a</sup>	2	37.25 <sup>a</sup>	2	13.17 <sup>a</sup>
						<i>Linear</i>						
1	27.0	7.86	670	74.92	1463	$b_1$	1	14.37 <sup>a</sup>	1	50.74 <sup>a</sup>	1	17.50 <sup>a</sup>
2	63.0	7.86	280	123.2	611.3	$b_2$	1	33.45 <sup>a</sup>	1	23.77 <sup>a</sup>	1	8.85 <sup>b</sup>
3	27.0	14.54	168	34.90	681.3	<i>Cross</i>						
4	63.0	14.54	90	73.69	365.8	$b_{12}$	1	5.21 <sup>c</sup>	-	BER <sup>d</sup>	-	BER <sup>d</sup>
						<i>Quadratic</i>						
						$b_{11}$	-	BER <sup>d</sup>	-	BER <sup>d</sup>	-	BER <sup>d</sup>
5	19.5	11.20	332	22.64	1033	$b_{22}$	-	BER <sup>d</sup>	-	BER <sup>d</sup>	-	BER <sup>d</sup>
6	70.5	11.20	145	104.3	451.1	Residual	6		7		7	
7	45.0	6.48	403	92.09	727.6	lack of fit	5	38.56	6	5.70	6	26.09
8	45.0	15.92	102	57.37	453.3	pure error	1		1		1	
						Total model	9		9		9	
<i>Center points</i>						$R^2$ <sup>e</sup>		0.898		0.914		0.790
						adj- $R^2$ <sup>f</sup>		0.848		0.890		0.730
9	45.0	11.20	198	78.31	618.8	pred- $R^2$ <sup>g</sup>		0.587		0.813		0.514
10	45.0	11.20	215	84.65	668.9	adeq pre <sup>h</sup>		11.73		15.49		9.240

705 <sup>a</sup>  $p \leq 0.01$ .

706 <sup>b</sup>  $p \leq 0.05$ .

707 <sup>c</sup>  $p \leq 0.1$ .

708 <sup>d</sup> BER, the removed variable by “backward elimination regression” procedure.

709 <sup>e</sup>  $R^2$ , coefficient of determination.

710 <sup>f</sup> adjusted  $R^2$ .

711 <sup>g</sup> predicted  $R^2$ .

712 <sup>h</sup> adequate precision.

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726 **Table 3**  
 727 Mean values of SCT, SEC and SWC, *F* values and the effects of temperature and flow rate on SCT, SEC and SWC  
 728 measured at stage 2

Runs	<i>2<sup>nd</sup> stage</i>					Source of variance	<i>F</i> values and effect of independent variables					
	Independent variables		Dependent variables				SCT		SEC		SWC	
	Temp. (°C)	Flow rate (m <sup>3</sup> /h)	SCT (s)	SEC (MJ)	SWC (L)		DF	<i>F</i>	DF	<i>F</i>	DF	<i>F</i>
<i>Factorial points</i>						Model	5	63.01 <sup>a</sup>	4	12.09 <sup>a</sup>	3	77.24 <sup>a</sup>
						<i>Linear</i>						
1	27.0	7.86	623	69.66	1360	<i>b</i> <sub>1</sub>	1	172.7 <sup>a</sup>	1	0.20 <sup>b</sup>	1	198.3 <sup>a</sup>
2	63.0	7.86	180	79.18	393.0	<i>b</i> <sub>2</sub>	1	108.8 <sup>a</sup>	1	26.37 <sup>a</sup>	1	19.49 <sup>a</sup>
3	27.0	14.54	232	48.19	940.9	<i>Cross</i>						
4	63.0	14.54	42	34.39	170.7	<i>b</i> <sub>12</sub>	1	15.28 <sup>c</sup>	-	BER <sup>e</sup>	-	BER <sup>e</sup>
						<i>Quadratic</i>						
<i>Axial points</i>						<i>b</i> <sub>11</sub>	1	13.47 <sup>c</sup>	1	8.59 <sup>c</sup>	1	13.92 <sup>a</sup>
5	19.5	11.20	438	29.87	1363	<i>b</i> <sub>22</sub>	1	12.75 <sup>c</sup>	1	4.11 <sup>d</sup>	-	BER <sup>e</sup>
6	70.5	11.20	35	25.17	108.9	Residual	4		5		6	
7	45.0	6.48	384	87.75	693.3	lack of fit	3	111.4	4	61.69	5	100.4
8	45.0	15.92	83	46.68	368.9	pure error	1		1		1	
						Total model	9		9		9	
<i>Center points</i>						<i>R</i> <sup>2f</sup>		0.988		0.906		0.975
						adj- <i>R</i> <sup>2g</sup>		0.972		0.831		0.962
9	45.0	11.20	140	55.37	437.5	pred- <i>R</i> <sup>2h</sup>		0.911		0.626		0.926
10	45.0	11.20	145	57.09	451.1	adeq pre <sup>i</sup>		21.70		10.51		23.97

729 <sup>a</sup>  $p \leq 0.01$ .

730 <sup>b</sup> The term was a hierarchical term added after BER (backward elimination regression) process.

731 <sup>c</sup>  $p \leq 0.05$ .

732 <sup>d</sup>  $p \leq 0.1$ .

733 <sup>e</sup> BER, the removed variable by “backward elimination regression” procedure.

734 <sup>f</sup>  $R^2$ , coefficient of determination.

735 <sup>g</sup> adjusted  $R^2$ .

736 <sup>h</sup> predicted  $R^2$ .

737 <sup>i</sup> adequate precision.

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752 **Table 4**  
 753 Mean values of TCT, TEC and TWC, *F* values and the effects of temperature and flow rate on TCT, TEC and TWC  
 754 measured at stage 2

Runs	<i>Total cleaning stage (1<sup>st</sup> + 2<sup>nd</sup> regions)</i>					Source of variance	<i>F</i> values and effect of independent variables					
	Independent variables		Dependent variables				TCT		TEC		TWC	
	Temp. (°C)	Flow rate (m <sup>3</sup> /h)	TCT (s)	TEC (MJ)	TWC (L)		DF	<i>F</i>	DF	<i>F</i>	DF	<i>F</i>
<i>Factorial points</i>						Model	3	23.37 <sup>a</sup>	3	20.67 <sup>a</sup>	3	29.29 <sup>a</sup>
						<i>Linear</i>						
1	27.0	7.86	1293	144.6	2823	<i>b</i> <sub>1</sub>	1	30.25 <sup>a</sup>	1	17.94 <sup>a</sup>	1	68.75 <sup>a</sup>
2	63.0	7.86	460	202.4	1004	<i>b</i> <sub>2</sub>	1	34.69 <sup>a</sup>	1	33.78 <sup>a</sup>	1	14.38 <sup>a</sup>
3	27.0	14.54	400	83.09	1622	<i>Cross</i>						
4	63.0	14.54	132	108.1	536.4	<i>b</i> <sub>12</sub>	1	5.16 <sup>c</sup>	-	BER <sup>d</sup>	-	BER <sup>d</sup>
						<i>Quadratic</i>						
<i>Axial points</i>						<i>b</i> <sub>11</sub>	-	BER <sup>d</sup>	1	10.30 <sup>b</sup>	1	4.74 <sup>c</sup>
5	19.5	11.20	770	52.51	2396	<i>b</i> <sub>22</sub>	-	BER <sup>d</sup>	-	BER <sup>d</sup>	-	BER <sup>d</sup>
6	70.5	11.20	180	129.5	560.0	Residual	6		6		6	
7	45.0	6.48	787	179.8	1421	<i>lack of fit</i>	5	76.54	5	9.20	5	32.28
8	45.0	15.92	185	104.1	822.2	<i>pure error</i>	1		1		1	
						Total model	9		9		9	
<i>Center points</i>						<i>R</i> <sup>2</sup> <sup>e</sup>		0.921		0.912		0.936
						<i>adj-R</i> <sup>2</sup> <sup>f</sup>		0.882		0.868		0.904
9	45.0	11.20	360	141.8	1120	<i>pred-R</i> <sup>2</sup> <sup>g</sup>		0.723		0.717		0.812
10	45.0	11.20	338	133.7	1056	<i>adeq pre</i> <sup>h</sup>		12.82		12.36		14.77

755 <sup>a</sup> *p* ≤ 0.01.

756 <sup>b</sup> *p* ≤ 0.05.

757 <sup>c</sup> *p* ≤ 0.1.

758 <sup>d</sup> BER, the removed variable by “backward elimination regression” procedure.

759 <sup>e</sup> *R*<sup>2</sup>, coefficient of determination.

760 <sup>f</sup> adjusted *R*<sup>2</sup>.

761 <sup>g</sup> predicted *R*<sup>2</sup>.

762 <sup>h</sup> adequate precision.

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**Highlights**

- > Cleaning in place protocol was optimised in terms of cleaning inputs
  
- > A two step cleaning in place protocol was proposed for industrial cleaning processes
  
- > The first was application of water at ambient temperature in the 1<sup>st</sup> step
  
- > The second was application of hot water in the 2<sup>nd</sup> step at the same velocity
  
- > The proposed protocol remarkably decreased energy consumption and waste water amount