REMOVAL KINETICS OF PINK GUAVA PUREE FOULING DEPOSIT FROM A STAINLESS STEEL SURFACE DURING ALKALINE CYCLE

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ABSTRACT

The development of economic CIP process requires comprehensive studies of the removal kinetics of the fouling deposit. Using pink guava puree (PGP) fouling deposits as a fouling deposit physical model, the removal kinetics from the stainless steel surface were determined by using a laboratory-scale cleaning test rig. The fouled test object is located at the center of the developed pipe flow. The influence of temperature (35-70°C), fluid velocity (0.6-1.5m/s at Reynolds numbers range of (Re=4 x 10^4 to 1.8 x 10^5)), and NaOH concentration (0-2.0wt%) on cleaning behavior during alkaline cycle were evaluated. For the first time, rapid stage and gradual stage are used to describe the cleaning process during the alkaline cycle. It is suggested that cleaning parameters for alkaline cycle are 70 °C, 1.2 m/s, 1.5 wt% NaOH, with t_{rapid}=2 minutes.

INTRODUCTION

Cleaning-in-place (CIP) is an important process in food factories to maintain a hygienic processing environment. The fouling deposit that builds up frequently on heated surface of the processing equipment can cause contamination to food products (Bott, 1995). Different kinds of food products generate different characteristics of fouling deposit (Fryer, P. and Asteriadou, 2009; Goode et al., 2013; Khalid et al., 2014; Khalid et al., 2015). Thus, each food processing plant should have a formulated CIP process to efficiently remove the fouling deposit. Selection of suitable and optimum cleaning methods are very important to avoid any chemical wastage and to minimize the downtime (Khalid et al., 2014). The conventional CIP process involves eight cycles, which are: (1) removal of gross debris, (2) pre-rinse, (3) detergent recirculation, (4) intermediate rinse, (5) second detergent recirculation (optional), (6) intermediate rinse, (7) disinfection and (8) final rinse (Tamime, 2008). Sometimes, a second detergent recirculation is not needed because the first detergent recirculation is enough with sufficient cleaning time (Tamime, 2008).

Bird and Espig, (1994) applied conventional CIP and a laboratory-scale cleaning apparatus rig to investigate effects of NaOH concentrations (0-2.0wt%), temperatures (40-70°C), and fluid velocities (0.035-0.525m/s at Reynolds numbers range of (Re=3.4 x 10^2 to 5.1 x 10^3)) upon the cost of cleaning for milk fouling. It took 35 minutes of total cleaning time to complete CIP cycles in food industry, which includes 5 minutes of pre-rinse, 15 minutes of alkaline recirculation, 3 minutes of water rinse and 5 minutes of acid recirculation (Bird and Espig, 1994). Several papers investigate the cleaning performance of alkaline-based detergents on coconut milk fouling deposit (Law et al., 2009), pink guava juice fouling deposit (Ho et al., 2010; Ong et al., 2012) and tomato puree fouling deposit (Ab. Aziz, 2007). In their studies, several combinations of parameters, which are fluid velocity, temperature and chemical concentration were used during the cleaning test. This is similar to industry practice (Bird and Espig, 1994). Findings by Law et al. (2009) showed that a temperature of 80°C, a flow rate of 2.0 l/min and 2%V/V NaOH can be applied to remove the coconut milk fouling deposits. Pink guava juice fouling deposit can be cleaned at a temperature of 65°C, a flow rate of 1.0 l/min and 0.4%V/V Na_2O (Ho et al., 2010). Meanwhile, findings from Ab. Aziz (2007) showed that a temperature of 70°C and flow rate of 2.3 L/min water can remove the tomato puree fouling deposit from the surface.

There are several works reported on the modification of the conventional CIP cycles, in order to improve the cleaning performance. For instance is by adding the pigging process where the remaining product or fouling deposit is pushed out from the pipeline, by using compressed air, water or other liquids. This pigging process can be added before the CIP process or added in between the CIP cycle ("Cleaning-in-place", 2010). Ice pigging was used for cleaning in several industrial applications such as drinking water industry, chemical industry and utilities industry ("Ice Pigging", 2015). The conventional CIP process is a steady state flow process in which the fluid velocity used for every cycle is constant. Studies conducted by Gillham et al. (1999, 2000) used pulsed flows to increase the cleanability of the process equipment. In the work of Gillham et al. (2000), cleanability experiments were performed using 0.5 wt% NaOH, 50 °C and a flow rate of 100 ml/min (Re=585).

Cleaning using pulsing frequency of 2 Hz increased the heat transfer up to 100%. The results shows that pulsed flow cleaning can be considered as an alternative strategy to produce a high velocity circulation of the cleaning solution in the CIP process. However, this method needs extra equipment (pulsing unit) in order to generate the pulsing effect. Processing of a carbohydrate-based raw material into the consumer products often creates viscous pastes, which lead to fouling deposit formation, particularly on the heat exchangers surfaces (Bird & Bartlett, 1995). PGP fouling deposit, a carbohydrate-based fouling deposit, was chosen as the physical fouling deposit model for this work due to the lack of research relating to suitable CIP process for PGP factory. Whilst CIP processes for protein-based fouling deposit (Gillham et al., 1999; Gillham et al., 2000; Christian and Fryer, 2004; Christian and Fryer, 2006; Liu et al., 2006a; Liu et al., 2006c) have been extensively studied, carbohydrate-based fouling deposit removals have received little attention. Only a few studies on carbohydrate-based fouling deposit cleaning are reported (Law et al., 2009; Ho et al., 2010; Ong et al., 2012).

In this paper, we want to emphasize that there is no additional equipment or process added to the CIP process, and effective cleaning can be achieved using the conventional CIP process with suitable cleaning condition. This is more economical and can shorten the downtime. In this paper, alkaline cycle is the area of interest for which the effectiveness of the whole cleaning process in food industry is greatly affected by this step (Bird and Espig, 1994). This study was carried out to find the best cleaning condition for removing the PGP fouling deposit during the alkaline cycle. The PGP fouling deposit removal kinetics from the stainless steel surface was determined using different cleaning parameters combination of NaOH concentrations (0-2.0wt %), cleaning temperatures (35 °C to 70 °C) and fluid velocities (0.6-1.5m/s) at Reynolds numbers range of (Re=4 x 10^4 to 1.8 x 10^5).

MATERIALS AND METHOD

Raw Material

The PGP used in the experiments was provided by Sime Darby Beverages Sdn Bhd that is located in Setiawan, Perak. Before being packed into aseptic bags in a carton, an Ultra High Temperature (UHT) process has been applied to the purees. The composition of the PGP and PGP fouling deposit are shown in Table 1.

Preparation of fouled test object

Fouling deposit preparation method has been developed, which enables reproducible, similar and uniform carbohydrate-based fouling deposit to be produced for use in every cleanability experiment (Khalid et al., 2014). The method was proposed by Liu et al. (2006a, 2006b) was adapted in this work to prepare the physical model of PGP fouling deposit. The test object is 1.5cm wide x 9.0cm long with thickness of 2mm (Refer Fig. 2). Two grams of PGP was evenly spread on the test object of 1.5cm width x 4.5cm long considering visible area of the test section, resulting in 675 mm^2 of surface area. Then, it was heated in a convective oven at 100°C for 1 h to form a hard and dry food deposit with a thickness of 1mm, to resemble the industrial fouling deposits. The PGP fouling deposit produced was tenacious, representing a tough cleaning problem in PGP industry.

Table 1. Composition of the PGP and PGP fouling deposit (Chan and Ab. Aziz, 2011)

Component	PGP (%)	PGP Fouling deposit (%)
Moisture	94.6367±0.03	84.7859±1.41
Ash	0.4409±0.17	0.6310±0.02
Protein	0.7727±0.04	1.2639±0.16
Fat	0.1937±0.02	0.1786±0.01
Fiber	0.8631±0.04	1.5105±0.15
Carbohydrate	3.3678	11.63

The laboratory-scale cleaning test rig

The laboratory-scale cleaning test rig (Fig. 1), was divided into three main parts; (1) storage tank, (2) test section and (3) flow channel. This rig was designed and constructed at the Process and Food Engineering laboratory of the Faculty of Engineering, the Universiti Putra Malaysia, Malaysia (Khalid et al., 2015). The rig was connected to two stainless steel tanks (300 L each) that were used to store water, and another stainless steel tank (55 L) containing a heating element used to store and to heat the cleaning solution. The test section enables real-time monitoring of the removal activities and the effect of chemical reaction and fluid mechanics on the cleaning kinetics can be deduced. The flow channel is designed to permit connection of the conduit and provides a continuous flow during CIP process. In this design, CIP environment is considered. This rig can operate at fluid velocity varying from 0.5 m/s to 2.0 m/s for closed conduits and capable of withstanding contact with detergents and disinfectants at the cleaning temperatures (20 °C to 70 °C).

Test section

The fouled test object was then installed inside the test section. The test section was made from glass and was assembled permanently into a transparent glass rectangular box. The glass rectangular box would act as an external lens to eliminate the optical power as discussed in Khalid et al., (2015). This test section provided easy optical access for recording the cleaning process from both the top and the side view. The schematic diagram of the test section is shown in Fig. 2.
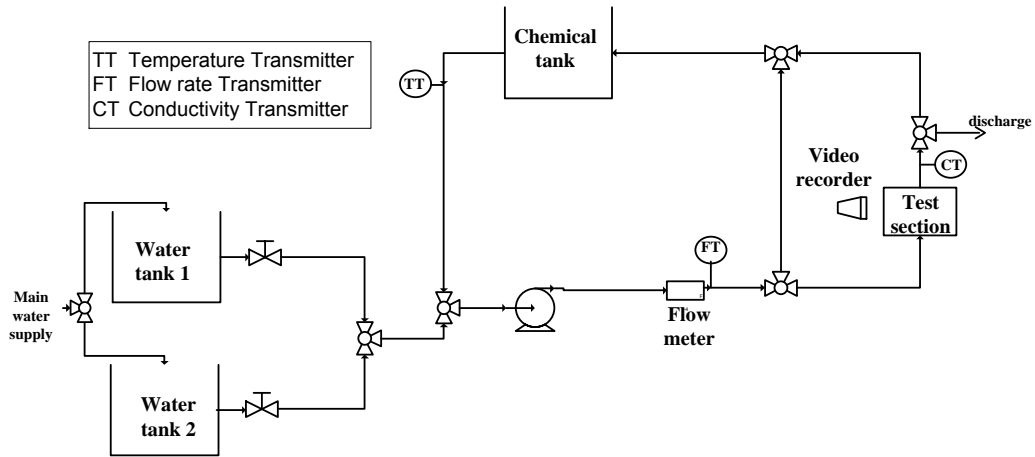
Fig. 1 Piping and Instrumentation Diagram of Cleaning Test Rig (Khalid et al., 2015)
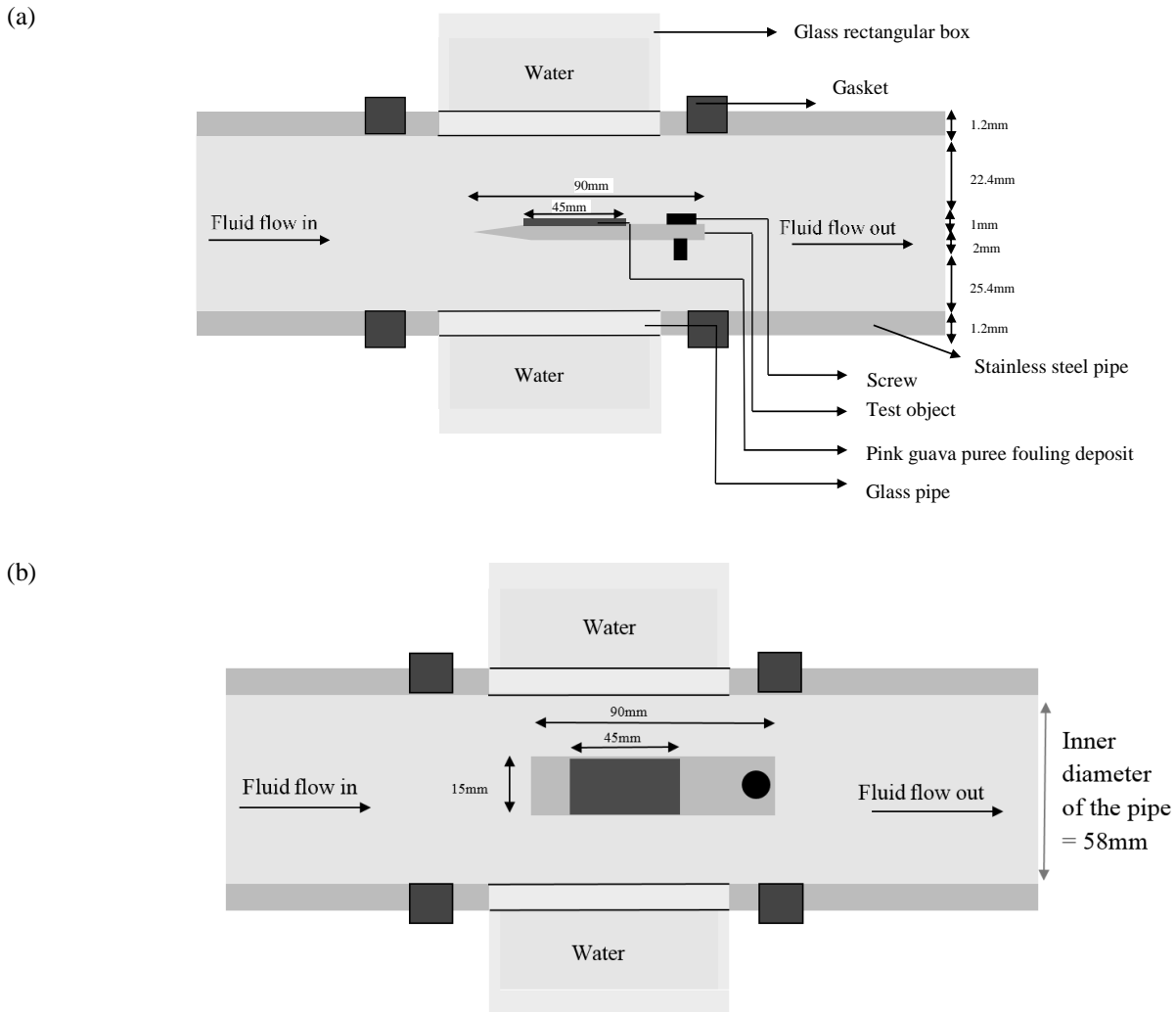
(a)

(b)

Fig. 2 Schematic Diagram of Test Section (a) side view and (b) top view (Khalid et al., 2015)

CIP procedures: Removal kinetics

The test section with the fouled test object was then installed within the laboratory-scale cleaning test rig. NaOH solution was heated to a desired temperature, and was pumped into the conduit, passing through the test section and then recirculated until the removal of the PGP fouling deposit was completed. The cleanability experiments were performed using a combination of NaOH solution of 0 to

2.0wt%, cleaning temperatures of 35 to 70°C and fluid velocities of 0.6 to 1.5m/s. Each cleaning condition was performed in triplicate. In this work, the highest temperature, NaOH concentration and fluid velocity used are 70°C, 2.0wt% of NaOH and 1.5m/s because these are the maximum cleaning parameters that had been utilized widely in the food industry. Thus, 70°C, 2.0wt% of NaOH, and 1.5m/s were chosen as the highest cleaning parameters for this work. 0.6m/s is chosen as the lowest fluid velocity because this parameter is the minimum fluid velocity needed to ensure that the cleaning fluid fully filled the pipe during cleanability experiments. 35°C (ambient temperature) and water (0wt% of NaOH) are selected to investigate the cleaning performance without heat and NaOH. A video camera (Panasonic, HDC-SD100) was placed on top of the test section to record the removal kinetics of the fouling deposit and its removal time. The video recording was started at the same time as when the cleaning solution started to flow inside the rig. The cleaning time is recorded when the PGP was observed to be 100% physically cleaned through the video camera screen. In this work, we defined that the fouled surface is not effectively cleaned if the cleaning time exceeds 180 min. In the food industry, it is not economical to perform CIP with a long cleaning time as it increases the cleaning cost and downtime. The recorded video was converted into 1-minute interval images. The images of the cleaning process were extracted from the recorded video and were analyzed using the Image J software (National Institutes of Health

(NIH), Bethesda, Maryland, USA). The remaining area of the PGP fouling deposit on the test object was measured to generate a cleaning profile for every cleanability experiment.

RESULTS AND DISCUSSIONS

Evaluation of cleaning profiles

The cleaning profile can be explained at two stages (rapid and gradual stages). Rapid stage is defined when fouling deposit is removed at high removal rate (removal rate of 0.5–5.9 cm^2/min) and the removal process occurred at every minute. Meanwhile, gradual stage is defined when fouling deposit is removed gradually and the cleaning progress is not too often. For the gradual stage, the removal rate is 0-0.4 cm^2/min. Step removal occurred during gradual stage, where the fouling deposit was removed step by step over a certain delay time. From cleaning profile of the PGP fouling deposit at 35 °C, with NaOH concentration of 2.0 wt% and a fluid velocity of 0.6 m/s (Fig.3), a 20-minute rapid stage was observed and followed by 160 minutes of the gradual stage. During the gradual stage, the pieces or parts of PGP fouling deposit removed a delay between each removal. Similar step removal can be observed during the removal of carbohydrate- based deposit, such as tomato puree fouling deposit in the work by Ab. Aziz et al., (2007). Finally, the cleaning time was recorded when 100% PGP fouling deposits were physically removed.
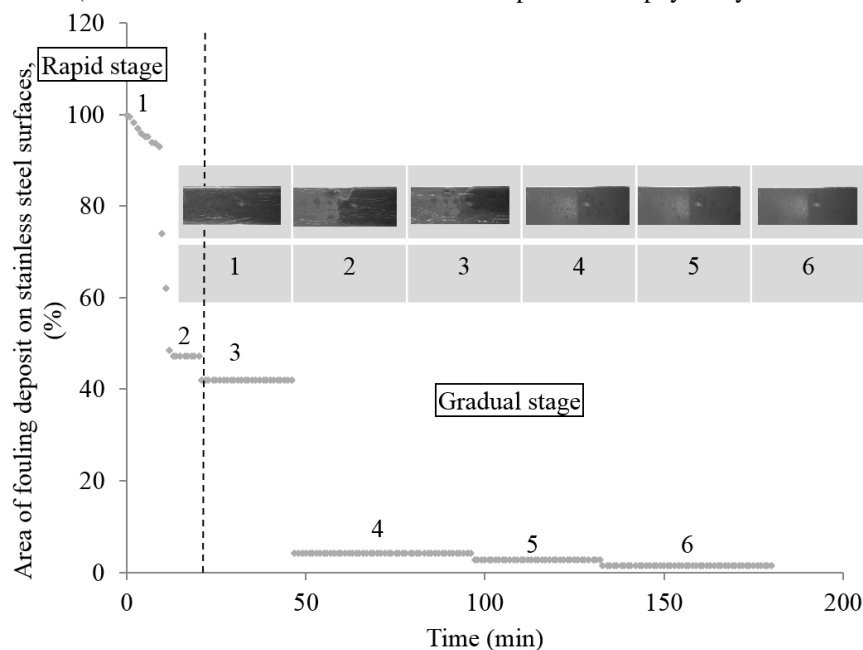

Fig. 3 Cleaning profile at 35 °C and 2.0 wt% NaOH with a fluid velocity of 0.6 m/s.

Removal kinetics model

Lelièvre et al. (2002b) have developed a cleaning kinetics model to predict the cleaning efficiency of Bacillus spores under steady flow condition in a stainless steel pipe. During their cleanability experiments, there were spores that were removed from the system and also spores that could adhere onto the surface. The model proposed by

Lelièvre et al. (2002b) described the cleaning of Bacillus spores which is based on a process combining removal and deposition as a function of time (Eq. (1)).

$$\frac{dN(t)}{dt} = k_1 \lfloor N_0 - N(t) \rfloor - k_2 \lfloor N(t) - N_R \rfloor \qquad (1)$$

Where k_1 is the effective deposition rate constant, where the surface density of spores removed is the difference between the initial surface density N_0(CFU/cm) and surface density at time t, N(t), N_R (CFU/cm) is adhering spores that would still remain on the surface, k_2 is the effective removal rate constant. N(t) (CFUcm^{-2}), the surface density of the spores at time t, was chosen to describe the cleaning kinetics of surfaces soiled by Bacillus spores.

The cleanability results showed that the amount of adhering spores on the cleaning control pipes was negligible (<1 CFU for 50 cm^2). Therefore, the deposition phenomenon could be neglected and then k_1 would be null. Thus, Lelièvre et al. (2002b) wrote the model for cleaning kinetics of Bacillus spores as in Eq. (2).

$$N(t) = N_0 \exp(-k_2 t) \qquad (2)$$

This simple model was similar to the first-order equation introduced by Jennings et al. (1957) to model the cleaning kinetics of food soil. Grant et al. (1996) and Dickinson et al. (1995) also used the same model proposed by Jennings et al. (1957, as cited by Lelièvre et al., 2002b). Each researcher uses different monitoring parameters for their study. For instance, Lelièvre et al. (2002b) and Dickinson et al. (1995) used the values of the surface density of adhering spores, while Jennings et al. (1957) and Grant et al. (1996) used the values of the mass of milk fouling residues to model the cleaning kinetics.

The cleaning kinetics model (Eq. (2)) proposed by Lelièvre et al. (2002b) was adapted in this cleanability work (Eq. (3)), in which the area of the PGP fouling deposit remained. A(t) was used as the parameter of the model replacing N(t). The term k_2 is the effective removal rate constant. This cleaning kinetics model was used to determine the $k_{2,rapid}$ and $k_{2,gradual}$, which represent the removal rate constants for the rapid stage and the gradual stage. At time t, the area of the PGP fouling deposit removed is the difference between the initial area A_0 and A(t).

$$A(t) = A_0 \exp(-k_2 t) \qquad (3)$$

Equation (3) was used to plot a linear graph of ln A(t) against time and k_2 was quantified from the gradient of the line. Fig. 4 and Fig. 5 showed the linear graph of ln A(t) against time for the rapid and the gradual stages, for which cleaning was performed at a temperature of 35 °C, a NaOH concentration of 2.0 wt% and a fluid velocity of 0.6 m/s. Fig. 4 and Fig. 5 are generated from the cleaning profile in Fig.3. One-stage cleaning combining rapid and gradual stages is shown in Fig. 6.

Relationship between cleaning parameters with the effective removal rate constant

In order to predict the removal efficiency of the PGP fouling deposit, it is important to define the effective removal rate constant, k_2 against the cleaning parameters

(NaOH concentration, temperature and fluid velocity), as it is closely related to the cleaning rate. An analysis of variance was performed to evaluate the effect of different NaOH concentrations on the values of $k_{2,rapid}$ and $k_{2,gradual}$. Correlations are considered statistically significant at a 95% confidence interval in which the P value is less than 0.05.
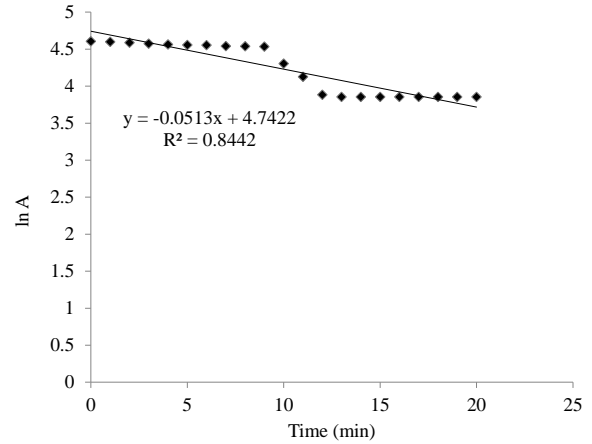

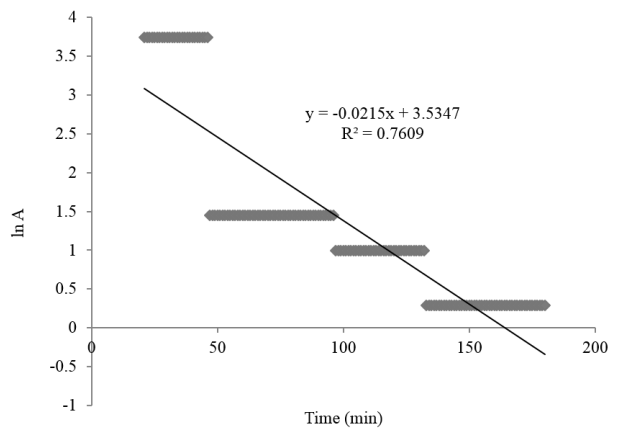Fig. 4 ln A(t) against time for the rapid stage at 35 °C and 2.0 wt% NaOH with a fluid velocity of 0.6 m/s.

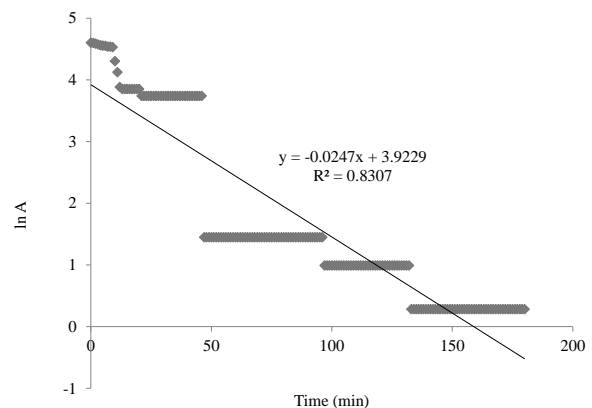Fig. 5 ln A(t) against time for the gradual stage at 35 °C and 2.0 wt% NaOH with a fluid velocity of 0.6 m/s.

Fig. 6 ln A(t) against time for the one-stage cleaning at 35 °C and 2.0 wt% NaOH with a fluid velocity of 0.6 m/s.

Early cleaning studies suggested that increase in chemical concentrations will increase the removal rate (Liu et al., 2007; Law et al., 2009; Ho et al., 2010). The increase in chemical concentration will reduce the intermolecular forces within the structure of the deposit and further assist the deposit removal (Law et al., 2009; Ho et al., 2010). Ho et al. (2010) also stated that alkaline detergent allowed greater driving force for chemical diffusion and increased the cleaning rate significantly. Cleaning studies conducted by Karlsson et al. (1998) in the removal of the β-lactoglobulin from stainless steel surfaces showed that increasing the NaOH concentration from 0.1 to 0.2 mg/ml increased the removal rate, where the amount of β-lactoglobulin fouling remained after cleaning decreased.

Table 2 shows the dependency of $k_{2,rapid}$ on the NaOH concentration when cleaning at velocity of 0.6m/s and at a temperature of 70°C. The $k_{2,rapid}$ data indicate that different NaOH concentrations applied during the cleaning had significant effect on the rapid stage at these cleaning conditions (p_{value}=0.01). It is found that the removal rate is higher at 2.0wt% NaOH with shorter average t_{rapid} (5 minutes). As NaOH concentration increased, the amount of particles (NaOH molecules and water) colliding with each other also increased, which improved the chemical reactions. These chemical reactions weakened the intermolecular forces within the structure of the PGP fouling deposit (cohesive forces), which subsequently increased cleaning efficiency in the rapid stage. When 1.0 wt% NaOH was used, 70 % of increment of $k_{2,rapid}$ can be observed compared to water. Furthermore, $k_{2,rapid}$ increased 134% when 2.0wt% NaOH is used as cleaning solution.

Similar results were observed at the rapid stage at a fluid velocity of 0.9m/s and at temperature of 35°C (p_{value}=0.037). However, no significant difference was found between NaOH concentration of 1.5wt% and 2.0wt% (Table 2) with the average t_{rapid} recorded for both concentrations were 9 minutes, it can be concluded that at 0.9m/s and 35°C, 1.5wt% of NaOH is sufficient for rapid stage cleaning. Different NaOH concentrations show no significant effect on the $k_{2,rapid}$ at other cleaning conditions, for instance at a temperature of 50°C and fluid velocity of 0.9m/s (Table 2).

At the gradual stage, different NaOH concentrations show significant effect on the $k_{2,gradual}$ at a fluid velocity of 0.6 m/s and at a temperature of 70 °C (p_{value}=0.039)(Table 2). This indicated that the high temperature of 70°C, contribute to the increased chemical reaction during gradual stage at a fluid velocity of 0.6m/s. Additionally, at 2.0wt% NaOH, higher removal rate was recorded. Different NaOH concentrations show no significant effect on the $k_{2,gradual}$ at other cleaning conditions. This is shown in Table 2 at a temperature of 70°C and fluid velocity of 0.9m/s.

Mechanical action is needed to remove the fouling deposit from the surface of the process equipment. The hydrodynamics force generated from the flow will drag the fouling deposit from the stainless steel surface by overcoming the interfacial force or adhesiveness force between the PGP fouling deposit and the stainless steel surface. Researches have been conducted on the influence of hydrodynamics effect on cleaning efficiency (Grassoff, 1997; Gillham et al., 1999; Lelièvre et al., 2002a; Friss & Jensen, 2002; Lelièvre et al., 2003; Jensen et al., 2005; Liu et al., 2006a; Blel et al., 2008). The results show that hydrodynamic effect is one of the cleaning factors in the CIP process due to the fluid shear force near the wall.

An analysis of variance performed on the values of $k_{2,rapid}$ and $k_{2,gradual}$ was to evaluate the potential effect of different fluid velocities during cleaning at the different stages. The fluid velocities applied during the cleanability experiment with water only had a significant effect on $k_{2,rapid}$ (p_{value}=0.047) at a temperature of 70°C. However, Table 2 shows that there is no significant difference between 1.2m/s and 1.5m/s. This indicated that 1.2m/s is a sufficient water velocity for rapid stage cleaning at 70°C. The average $t_{gradual}$ at 1.2m/s was 178 minutes. Different fluid velocities showed no significant effect on the $k_{2,rapid}$ at other cleaning conditions, for instance at a temperature of 50°C with 1.0wt% NaOH (p_{value}=0.376). This is shown in Table 2.

Table 2 also shows that the fluid velocity applied during the cleanability experiment with water also had a significant effect on the $k_{2,gradual}$ (p_{value}=0.009) at a temperature of 50 °C. Higher value of $k_{2,gradual}$ was recorded at a high fluid velocity of 1.5m/s. Meanwhile, at 0.6m/s, 0.9m/s and 1.2m/s, the values were small, which is closer to 0. Table 2 shows that at 0.6m/s, 0.9m/s, 1.2m/s and 1.5m/s, the $k_{2,gradual}$ values were 0.012, 0.015, 0.016 and 0.482 respectively. The average $t_{gradual}$ at 1.5m/s is 10 minutes.

Different fluid velocities applied also gives significant effect on $k_{2,gradual}$ (p_{value} =0.046) at temperature of 35°C and with 1.0wt% NaOH, as shown in Table 2. Higher $k_{2,gradual}$ value was recorded at 1.2m/s. the cleanability experiment was not performed using NaOH at 1.5 m/s due to visibility restrictions. At a high velocity, visual inspection was not possible due to the micro bubbly effect that was caused by the chemical reaction. The average $t_{gradual}$ at 1.2m/s is 178 minutes. Different fluid velocities show no significant effect on the $k_{2,gradual}$ at other cleaning conditions. Table 2 shows that there is no significant effect on $k_{2,gradual}$ when cleaning was performed at temperature of 50°C with 1.5wt% NaOH.

The choice of optimal CIP condition for the alkaline cycle

The highest $k_{2,rapid}$ value ($k_{2,rapid}$ =0.455) was obtained when the cleaning was performed at 70 °C, 1.2 m/s and with 1.5 wt% NaOH. This is shown in Fig. 12. The average t_{rapid} is 2 minutes. As discussed in the relationship between chemical concentration and the cleaning temperature with the effective removal rate constant, NaOH concentration and temperature effects are important cleaning parameters in the rapid stage. In the rapid stage, swelling happens when fouling deposit is in contact with the alkaline solution. This process signifies the weakening of the intermolecular bonds within the fouling deposit, as well as

the bond between the fouling deposit and the surface (Liu et al., 2006a). Moreover, cleaning performed at high temperature of 70 °C will increase the chemical reaction rate. Studies performed by Christian and Fryer (2004), Ab Aziz (2007) and Khalid et al. (2014) had shown that the cleaning performance was greatly improved when the temperature was increased.

The highest $k_{2,gradual}$ value ($k_{2,gradual}$ =0.687) was achieved when cleaning was performed at 35 °C, 1.5m/s and with water (0wt% NaOH). This is shown in Fig. 12. The average $t_{gradual}$ is 10 minutes. The fouling deposits remained at this stage are very thin, which is less than 1mm (also called as debris). Thus, at this stage (gradual stage), fluid velocity effect is the most dominant parameter. High fluid velocity will generate a flat velocity profile with thinner boundary layer thickness, which can remove the debris easily during the gradual stage cleaning. Khalid et al. (2014) also stated that the debris remained on the stainless steel surface in the gradual stage need to be removed by high fluid velocity. Khalid et al. (2014) suggested 1.5m/s as the cleaning velocity. Romney (1990) also stated that 1.5 m/s is an optimum velocity in most cases of CIP. Moreover, Christian and Fryer, (2004) used high flow rate of 2.3 l/min to remove the milk fouling deposit, as the deposit removal after swelling stage is dependent on the physical factor. At gradual stage, alkaline solution is not needed. Thus, alkaline cycle can be stopped as soon as the cleaning reached gradual stage. Therefore, alkaline cycle can be performed at 70 °C, 1.2 m/s, 1.5wt% NaOH, with shorter cycle time of 2 minutes.

CONCLUSIONS

Two cleaning stages (rapid and gradual) were identified, in the cleaning profile, which influence the PGP fouling deposit removal kinetics. A model by Lelièvre et al. (2002b) was employed to investigate how the cleaning parameters (NaOH concentration, cleaning temperature and fluid velocity) affected the removal rate in both stages. The findings suggested that alkaline rinse cycle are 70 °C, 1.2 m/s, 1.5 wt% NaOH, with t_{rapid}=2 minutes. Therefore, by manipulating the cleaning parameters, CIP can be done in a conventional way without the need to modify the cleaning equipment and add more cleaning processes.

Table 2. Average values of $k_{2,rapid}$ and $k_{2,gradual}$

Variable	Average $k_{2,rapid}$ (1/min)	Average $k_{2,gradual}$ (1/min)	Standard deviation (1/min)	P value
NaOH concentration (wt%), at 70°C and 0.6m/s.				
0	0.058[a]		0.00	0.01
1.0	0.098[b]		0.03	
1.5	0.128[c]		0.04	
2.0	0.136[d]		0.02	
NaOH concentration (wt%), at 35°C and 0.9m/s.				
0	0.000[a]		0.00	0.037
1.0	0.038[b]		0.00	
1.5	0.055[c]		0.00	
2.0	0.055[c]		0.00	
NaOH concentration (wt%), at 70°C and 0.6m/s.				
0	0.017[a]		0.00	0.039
1.0	0.162[b]		0.03	
1.5	0.157[b]		0.02	
2.0	0.277[c]		0.10	
NaOH concentration (wt%), at 50°C and 0.9m/s.				
0	0.096[a]		0.00	0.507
1.0	0.236[a]		0.00	
1.5	0.191[a]		0.10	
2.0	0.160[a]		0.07	
NaOH concentration (wt%), at 70°C and 0.9m/s.				
0	0.013[a]		0.00	0.146
1.0	0.145[a]		0.03	
1.5	0.175[a]		0.02	
2.0	0.143[a]		0.03	
Fluid velocity (m/s), at 70°C with water.				
0.6	0.058[a]		0.00	0.047
0.9	0.124[b]		0.00	
1.2	0.175[c]		0.00	
1.5	0.171[c]		0.03	
Fluid velocity (m/s), at 50°C with water.				
0.6	0.012[a]		0.00	0.009
0.9	0.015[a]		0.00	
1.2	0.016[a]		0.00	
1.5	0.482[b]		0.17	
Fluid velocity (m/s), at 35°C with 1.0wt% NaOH				
0.6	0.006[a]		0.00	0.046
0.9	0.013[b]		0.00	
1.2	0.022[c]		0.00	
Fluid velocity (m/s), at 50°C with 1.0wt% NaOH				
0.6	0.074[a]		0.00	0.376
0.9	0.236[a]		0.00	
1.2	0.224[a]		0.00	
Fluid velocity (m/s), at 50°C with 1.5wt% NaOH				
0.6	0.026[a]		0.02	0.499
0.9	0.026[a]		0.01	
1.2	0.073[a]		0.01	

Values followed by the same letter within the same column are not significantly different from each other (p<0.05).

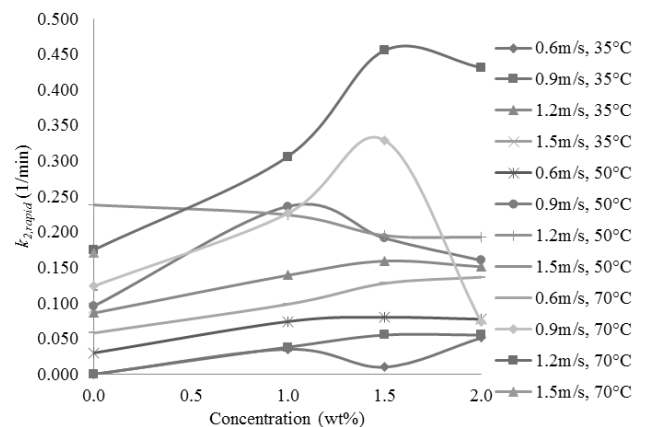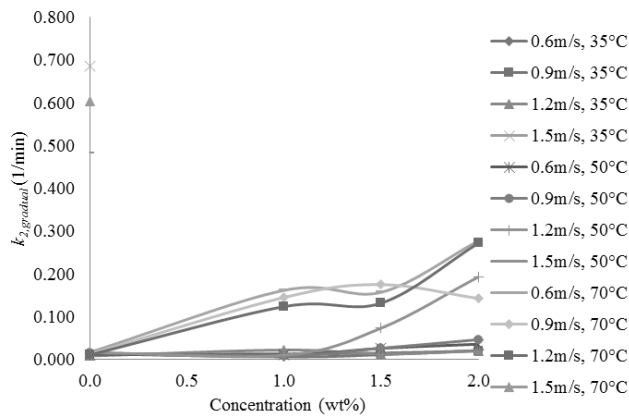Fig. 7 The removal rate constant ($k_{2,rapid}$) at different cleaning parameters

Legend: 0.6m/s, 35°C; 0.9m/s, 35°C; 1.2m/s, 35°C; 1.5m/s, 35°C; 0.6m/s, 50°C; 0.9m/s, 50°C; 1.2m/s, 50°C; 1.5m/s, 50°C; 0.6m/s, 70°C; 0.9m/s, 70°C; 1.2m/s, 70°C; 1.5m/s, 70°C. Y-axis: $k_{2,rapid}$ (1/min). X-axis: Concentration (wt%).

Fig. 8 The removal rate constant ($k_{2,\text{gradual}}$) at different cleaning parameters

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