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The impact of clean-in-place parameters on rinse water effectiveness and efficiency

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ABSTRACT

Although Cleaning-in-Place (CIP) is abundantly used throughout the food industry, it is recognized that CIP operations use significant amounts of water and energy. The overall objective of this investigation was to evaluate parameters needed to improve the effectiveness of water use during CIP pre-rinse. A pilot-scale CIP system was operated over a range of Reynolds number (Re) from 16,000 to 260,000, while evaluating the effectiveness of rinse water to remove a reconstituted skim milk residue film from stainless steel pipe surfaces. Rinse water effectiveness was quantified by comparing the protein concentration on the pipe surface after pre-rinse to the initial level. As the Re increased, the effectiveness of rinse step increased, but not in linear proportionality. The efficiency of the rinse water decreased significantly as the volume of rinse water increased. The results of this investigation provide the basis for reducing water and energy requirements during CIP operations.

1. Introduction

Cleaning is one of the most critical stages in quality control of food processing operations (Kulkarni et al., 1975). Failure to properly clean processing equipment not only increases the processing cost due to the decreased heat transfer coefficient, but also threatens plant operations with microbial contamination (Fryer et al., 2006; Gillham et al., 1999; Kulkarni et al., 1975; Mattila et al., 1990). Cleaning-In-Place (CIP) is a widely-used method of automated cleaning without the need for disassembling equipment, while reducing labor and time for cleaning (Seiberling, 1968). However, CIP systems require significant quantities of water, detergent, and energy. In addition, in-place cleaning generates large quantities of waste water, with the additional economic burden on the industry, and an environmental burden on the community (Lyndgaard et al., 2014). Optimization of CIP operations to reduce water and energy requirements, while maintaining hygiene of the CIP process is a worthwhile goal.

Over the past two decades, the basic understanding of the fouling and cleaning processes in dairy plants has increased considerably (Fryer and Robbins, 2005; Wilson, 2005; Xin et al., 2002). Novel approaches to enhance cleaning and reducing fouling have evolved, including modification of surfaces, pulsed flow, ozonated water rinse, electrolyzed oxidizing rinse water, and ultrasonic cleaning (Augustin et al., 2010; Boxler et al., 2013; Christian and Fryer, 2006; Dev et al., 2014; Gillham et al., 2000; Guzel-Seydim et al., 2000; Muthukumaran et al., 2004; Rosmaninho et al., 2007). All these methods require additional devices, capital investment, and in some cases; energy inputs. When compared to the aforementioned solutions, the adjustment of CIP control parameters (flow characteristics, water temperature, and contact time) to achieve improved cleaning efficiency while reducing water consumption would seem more practical for the industry.

Pre-rinse, as the first step of a CIP process, is to rinse fresh water through the processing system to drain until the discharge is clear (Seiberling, 1968). In addition to providing the initial soil removal, the pre-rinse may also assist the following alkaline cleaning step by wetting the severe deposits (Khaldi et al., 2015). The wetted deposit is consequently more vulnerable to the detergent (Goode et al., 2013). It is known that the direct physical force provided by the fluid would help the deposit to pass an energy barrier and detach (Fryer et al., 2006; Grant et al., 1997; Weidemann et al., 2014). Thus, any parameters influencing the physical force of the fluid would affect pre-rinse step. Reynolds number (Re) is commonly used to determine the flow characteristics (Singh and Heldman, 2013). Besides Re, some researchers believed other parameters to also be important in developing the prediction models for CIP operation.

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For example, Timperley and Smeulders (1987) concluded that flow velocity had a larger impact on the cleaning rate than Re. The correlation between wall shear stress (τ_ω) and the removal of the foulant from the surface has been demonstrated by many researchers (Sharma et al., 1992; Visser, 1970). Lelièvre et al. (2002) demonstrated that both the mean wall shear stress and the associated time-dependent fluctuation rate would impact the detachment of the foulant under turbulent flow conditions.

It is important to note that the papers mentioned above were based on the alkaline cleaning step which follows the pre-rinse step in CIP operation. Therefore, results from these studies would serve as good benchmark for investigating the mechanism of pre-rinse step, which has not been studied much by comparison. Furthermore, to our knowledge, there are no prediction models in literature to describe the impact of Re and its interactions with other CIP control parameters on the effectiveness of pre-rinse. Once built, these models can be used to optimize the CIP pre-rinse step, ensuring rinse effectiveness while reducing water/energy outlay by locating the optimum CIP parameter sets.

The objectives of this investigation were: (1) to establish the relationship between rinse water effectiveness and Reynolds Number at various temperatures and contact times, (2) to develop a relationship between the efficiency of water use and rinse water requirements, and (3) to develop recommendations on CIP parameters for maximum water effectiveness while reducing water and energy demands.

2. Materials and methods

2.1. Creating the deposit film

Rinsing experiments were conducted using pipe sections with known quantities of a deposit film. The deposit film was created using an established protocol (Fan et al., 2015). The deposit film was applied to pipe sections with three different diameters: 0.025 m (1 inch), 0.038 m (1.5 inch) and 0.050 m (2 inch). Seven pipe sections of the same diameter were combined to create a test line. The middle and two end sections of each test line were tested after each experiment. The deposit film contained nonfat-dry-milk (NFDM) (U.S. Foods, Inc., Rosemont, Ill., U.S.A.) reconstituted to 20% w/w in deionized water at ambient temperature. The pipe sections were filled with the reconstituted milk and held for 5 min at room temperature. The reconstituted milk was then removed and the pipe sections were allowed to drain at room temperature for 30 min. Next, each pipe section was placed in a 75 °C oven for 30 min to dry the deposit film. Three pipe sections were selected to be used in the CIP pre-rinse experiment. The remaining pipe sections were used to measure the protein content in the initial deposit film. The protein content of the deposit film was measured by washing the pipe interior using a sodium hydroxide solution. The protein assay was completed with QuantiPro™ Bicinchoninic Acid (BCA) (Sigma-Aldrich Co.).

2.2. Cleaning-in-place (CIP) pre-rinse

The cleaning-in-place (CIP) pre-rinse experiments were performed by mounting the fouled pipe sections on a test manifold, which is a part of a pilot-scale CIP system. The CIP system and test manifold were described in Fan et al. (2015). Tap water – pH from 7.2 to 7.7 (Model HI, 2020; Hanna Instruments, Inc., Woonsocket, RI., U.S.A.) – was used in this study. Tap water was recirculated through the CIP system, except for pipe sections with deposit films, until the flow rates (0.0016, 0.0028 or 0.0039 $m^3\ s^{-1}$) and temperatures (22, 45 or 67 °C) stabilized. Next, the flow of rinse water was directed to pipe sections with deposit films. Pre-rinse was programmed to be a single-pass step in this experiment, which means the rinse water was pumped to rinse the fouled pipe sections then drained directly without reusing. The contact time between the rinse water and the pipe sections with deposit films was controlled to 20 s or 60 s during this study. Due to the flow separation and gravity, nine velocities levels were achieved in three diameter pipes (0.025, 0.035 and 0.050 m) at three system set flow rates. At the same system set flow rate, the velocity of the flow in the 0.035 m (1.5 inch) pipe section is highest due to the gravity, while the velocity of the 0.025 m (1 inch) pipe section is the lowest. The pre-rinse experiment was performed three times from which three subsamples were obtained under each condition.

2.3. Data treatment

After each CIP pre-rinse, the test sections were disassembled and the residual deposit film was removed from each pipe section using a sodium hydroxide solution and the protein was quantified by Quantipro assay. The effectiveness of the CIP pre-rinse was determined from the percent residual film, which was calculated by comparing the protein content after pre-rinse to the protein content of the deposit film prior to rinsing (Equation (1) and Equation (2))

$$\text{Percent residual film (RF\%)} = 100\ [C/C_0] \tag{1}$$

$$\text{Rinse effectiveness} = 100 - \text{RF\%} \tag{2}$$

Where C ($\mu g\ cm^{-2}$) is the protein concentration after pre-rinse and C_0 ($\mu g\ cm^{-2}$) is the initial protein concentration.

The efficiency of water consumed during the pre-rinse step was evaluated from the rinse effectiveness data. Water efficiency (WE) was defined as the amount of deposit protein (kg) removed per unit volume (m^3) of water, as expressed in Equation (3)

$$WE = PR\ /\ WV \tag{3}$$

Where PR is the mass of protein removed per surface area ($kg\ m^{-2}$), which equals to C_0 minus C. WV is the volume of rinse water spent per surface area ($m^3\ m^{-2}$).

As suggested in Equation (4), the volume of water consumed (WV) was computed from the volumetric flow rate (V) of the rinse water and the contact time (t) between the rinse water and the pipe section, which was either 20 or 60 s in this study.

$$WV = (V)(t) \tag{4}$$

In order to minimize the impact of the system size on the models, both WE and WV were normalized to per fouled surface area. The fouled surface areas were calculated based on the inner diameter and length of the pipe sections.

2.4. Statistical analysis

SPSS.21 (IBM, Inc,. USA) statistics software was used for analysis of all data. The data have been reported as the means ± standard error. Analysis of covariance (ANCOVA) with 95% confidence interval was used to evaluate the statistical difference of the intercept and slope between the linear regressions. A one-way ANOVA with a 95% confidence interval was used to evaluate the statistical difference between the means.

3. Results and discussion

The influence of three CIP parameters (temperature, velocity,