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Mathematical modeling and cycle time reduction of deposit removal from stainless steel pipeline during cleaning-in-place of milking system with electrolyzed oxidizing water

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A B S T R A C T

The safety of raw milk largely depends on using a clean milking system during the milk production. The milking system cleaning process widely used on dairy farms is a highly automated process called cleaning-in-place (CIP), which comprises of four cycles: i) warm water rinse; ii) alkaline wash; iii) acid wash; and iv) sanitizing rinse before the next milking event. Electrolyzed oxidizing (EO) water is an emerging technology, which consists of acidic and alkaline solutions by the electrodialysis of dilute sodium chloride solution. Previous studies in our lab showed that EO water can be an alternative for milking system CIP. Despite the progress made to enhance the CIP performance and evaluate alternative CIPs, the mechanisms behind the cleaning processes were still largely unclear. Therefore, this study was undertaken to evaluate the deposit removal rate during the EO water CIP process using a stainless steel surface evaluation simulator. Deposit removal data from the simulator formed the basis for developing mathematical models to describe the deposit removal process during the CIP process with EO water. Stainless steel straight pipe specimens were placed at the end of undisturbed entrance length along the simulator pipeline. The mass of milk deposits on the inner surfaces of the specimens were measured using a high precision balance after the initial soiling, and then after certain time durations within the warm water rinse, alkaline wash, and acid wash cycles. A unified first order deposit removal rate model dependent on n^{th} power of remaining deposit mass was used for all three cycles. ATP bioluminescence method was also used as a validation approach at the end of each CIP cycle. Experimental results showed that the milk deposit on the inner surfaces of the specimens was removed rapidly by the warm water rinse within 10 s of rinse time. For the alkaline and acid wash cycles, the co-existence of a fast deposit removal at the beginning of the wash cycle and a slow deposit removal throughout the entire wash cycle was inferred. The proposed models matched the experimental data with small root mean square errors (0.23 mg/[(mg) (m^2)] and 0.07 mg/[(mg) (m^2)] for the upstream and downstream locations, respectively) and satisfactory percent error differences (3.67% and 0.93% for the upstream and downstream locations, respectively). Based on the experimental data and the proposed models, the time duration of the CIP process was shortened by 55% (10 s warm water rinse, 3 min alkaline wash and 6 min acid wash) and validated, which yielded an average deposit of 0.28 mg/[(mg) (m^2)] at the end of the CIP as compared with that of 0.29 mg/[(mg) (m^2)] at the end of the original CIP, to achieve a satisfactory CIP performance for the simulator.

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1. Introduction

The cleaning and sanitizing of milk processing pipelines are done using a highly automated cleaning-in-place (CIP) process to ensure the safety and quality of consumed milk. The CIP process does not require disassembly and reassembly of the pipelines and other fittings of the system and, therefore, is widely adopted in milking system due to its high automation. Conventional CIP for the milking system on a dairy farm, usually performed immediately after the milking event, consists of four cycles: i) warm water rinse; ii) alkaline wash; iii) acid wash; and iv) a sanitizing rinse just before

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the next milking event. The warm water rinse removes the milk residual on the inner surfaces, and the alkaline wash removes organic materials such as lipids and proteins; and the acid wash removes the mineral deposits and maintains the system in an acidified state to retard the growth of microorganisms (NDPC, 1993). The sanitizing circulation, just prior to the next milking event, ensures the sanitization of the milking system.

Electrolyzed oxidizing water is a novel technology, which provides alkaline and acidic solutions generated through the electrodialysis of dilute sodium chloride solution. The acidic EO water has the potential to reach a pH as low as 2.6 and an oxidation-reduction potential (ORP) as high as 1150 mV. The alkaline EO water possesses a pH as high as 11.4 and a negative ORP to −795 mV. Depending on needs, different properties of EO water can be generated by adjusting amperage and voltage. These properties of alkaline and acidic EO water fit the requirement of the milking system CIP (Hsu, 2005). Previous studies in our lab have demonstrated the efficacy of using EO water for the milking system CIP, both on a lab scale pilot milking system and on a commercial dairy farm (Dev et al., 2014; Wang et al., 2013). EO water has the advantage of having low operational cost and being environmentally benign.

Several factors affect the CIP performance, including the type and strength of the cleaning chemicals, the quantity and temperature of the cleaning solution, and the fluid dynamics in the milking system pipelines. Recommendations have been established to provide guidance in establishing a proper CIP condition (DPC, 2010), most of which greatly emphasize the importance of the first CIP cycle of warm water rinse in the removal of a large amount of deposits if conducted per the recommendations. However, the quantitative contribution of this warm water rinse cycle and the rest of the CIP cycles of alkaline and acid washes to the CIP process are largely unclear and undefined.

Investigations of the CIP models have been conducted for the past four decades and key efforts were made using alkaline solution such as sodium hydroxide to remove simulated soil such as whey protein concentrates and other proteinaceous compounds from stainless steel surfaces. Some pioneer studies were conducted by Harper (1972) and Schlussler (1976) in the model development. The first reported study using real milk to develop a mechanism-based model was conducted by Gallot-Lavallee and Lalande (1985) to describe the milk deposit removal in a plate milk pasteurizer holding section. The use of heated milk deposit greatly increased the deposit mass. One of the simulations described a cleaning process with a deposit mass of 0.3 kg of dry matter/m^2, which was orders of magnitudes higher than the depositing process of only raw milk passing through during the milking event. A swelling and removal two-stage model was proposed by Bird and Fryer (1991) using both whey protein concentrates and raw milk. Given the more consistent data collected with whey protein concentrates, more studies were performed using this simulated deposit to develop the foulant (i.e., deposit/soil) removal model. A three-stage cleaning process was proposed by Gillham et al. (1999) using NaOH in turbulent flow conditions to remove whey protein concentrated gel deposits. The three-stage cleaning process is now widely recognized by many researchers when using NaOH to remove the proteinaceous deposits; it includes: i) the swelling stage, during which the penetration of the cleaning fluid into the deposit and the conversion of the deposit into a removable form occurs; ii) the constant deposit removal rate stage, in this phase large amounts of deposit are removed, and iii) the decreasing deposit removal rate stage, herein deposits are removed until no detectable deposits remain on the contact surfaces (Xin et al., 2004).

Despite the progress made, there is still a knowledge gap − the CIP process in the previous studies was not fully represented; using only NaOH is not sufficient to represent the complete CIP process mechanism. Both alkaline and acidic solutions are needed in one complete CIP, since the alkaline solution is responsible for the organic residual removal and acid for the inorganic deposit. A more generalized mechanism-based mathematical model is needed to describe the milking system CIP. In order to achieve this, the contribution of each CIP cycle to the entire CIP process needs to be studied and understood. This can serve as the basis to optimize each cycle and/or the entire CIP process. In this study, experiments were performed using a surface evaluation simulator with stainless steel straight pipe specimens to model the deposit mass (soil) removal during the warm water rinse, alkaline wash, and acid wash cycles of the CIP process using EO water as the wash solution.

2. Materials and methods

2.1. Stainless steel surface evaluation by using the simulator

A surface evaluation simulator was specifically constructed for this study (Fig. 1). The simulator had altogether five stainless steel straight pipe specimens each 152.4 mm in length (Fig. 2). The stainless steel straight pipe specimen was 38.1 mm in outer and 36.8 mm in inner diameters. In addition, the simulator included an initial 1.5 m glass pipe for flow and deposit visualization, followed by a 4.6 m stainless steel straight pipe as entrance length for the flow to be fully developed. To determine the needed entrance length, SolidWorks® Flow simulation module (Version 2013, Dassault Systèmes SolidWorks Co., Waltham, MA) was used with the recommended flow velocity of 0.06 m/s (ASABE, 2011) to soil the simulator contact surfaces. Three out of five specimens were placed as evaluation specimens for the nearer to the inlet “upstream locations” consecutively after the entrance length. The distance between the end of specimen #1 and the beginning of specimen #2, as well as the end of specimen #2 and the beginning of specimen #3, was 1.1 m, hereby denoted as recovery sections. The length of the recovery section was established based on flow perturbations introduced by misalignment of rubber gaskets at connections using SolidWorks®; a 5% difference in the inner diameter was used for all the simulations (the rubber gasket shifted downward, upward, inner diameter larger or smaller cases were considered). Preliminary results showed that it took at most 0.8 m, which is much less than 1.1 m for the flow to recover for all cases. After specimen #3, there was a 1.5 m stainless steel straight pipe to straighten the

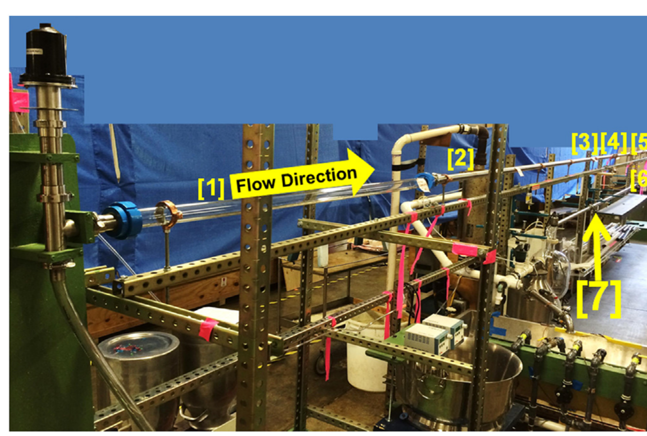

Fig. 1. Stainless steel surface evaluation simulator with specimen of 152.4 mm straight pipe test section. [1] Inlet glass visualization, 1.5 m; [2] Entrance length, 4.6 m; [3] Upstream locations (specimens #1, 2, and 3) of stainless steel straight pipe specimen, 152.4 mm; [4] Recovery section, 1.1 m; [5] Return line, 1.5 m; [6] Exit glass visualization, 152.4 mm and return elbow; [7] Downstream locations (specimens #4 and 5) of stainless steel straight pipe specimen, 152.4 mm.

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