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Poly-optimization of cleaning conditions for pipe systems and plate heat exchangers contaminated with hot milk using the Cleaning In Place method

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A B S T R A C T

Devices used in food industry that are connected by pipelines are usually cleaned using Clean In Place method. Such a system of cleaning generates high consumption of energy, water and requires the use of chemical cleaning solutions. In this study, we aimed to activate the physical factors in the process of cleaning and minimize the energy consumption. The variable factors considered within this study were flow velocity, pressure, temperature of the cleaning medium (pure water), and cleaning time. The effects of cleaning efficiency and the energy consumed in the cleaning process were taken as the criteria for the evaluation of the cleaning process in Clean In Place station. For the purpose of optimization, these evaluation criteria were opposed to each other; namely, they sought a high cleaning efficiency with a minimal input of energy. Both functions were based on a set of experimental results using the technique of experimental design. A 5-level experimental design, orthogonal and rotatable, was employed. These equations were used in multi-objective optimization process. A polyoptimal model of cleaning conditions was developed. Results were calculated by using Matlab scripts and showed a set of acceptable solutions on the plane of controllable variables (cleaning factors) because of accepted criteria (energy and cleanliness). The dominated and non-dominated points were appointed. These points described cleaning conditions for which it was possible to obtain a better cleanliness without increasing the amount of energy (the dominated points) and conditions for which we were not able to improve any of the tested criteria (the non-dominated points). Finally, the polyoptimal results defining the favorable effects of a cleaning fluid without the use of chemical agents were determined. The results obtained during this study are important from an ecological aspect of the effectiveness of the Cleaning in Place system and may be applied in real conditions for the development of cleaning programs of the analyzed objects (e.g. in a dairy industry for which these experimental studies have been carried out). The obtained set of optimal solutions constitute a basis for further studies in the aspect of energy consumed and an effectiveness of the cleaning process in Clean In Place system.

1. Introduction

Increasing environmental awareness has brought issues such as water scarcity and depletion of fossil fuels to the attention of the food and beverage industry (Pettigrew et al., 2015). Cleaning In Place (CIP) operation is a particularly energy and water intensive process in the food industry and has a negative impact on the environment. These procedures characterize with high energy and water consumption. Additionally, chemical cleaning solutions, which are used, are non-degradable biologically (Pettigrew et al., 2015; Tanmay et al., 2014). Cleaning processes are the largest contributor to the overall wastewater volume in food processing. This problem represents one of the components of sustainable development which is considered under the economic, environmental and social aspects. In the food industry sector, this not only means production of food that meets an appropriate quality and is

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List of symbols

E	energy requirements (kWh)
J	cleaning degree (−)
K	multicriterial function of optimization taking into account criteria of energy and cleanliness (−)
T	temperature of cleaning medium (°C)
V	volume of liquid (m^3)
k	proportional coefficient (−)
p	pressure (bar)
t	cleaning time (min)
u	fluid flow velocity ($m\ s^{-1}$)
w_E	balance coefficient of impact energy and the quality of cleaning (−)
Subscripts	
PHE	plate heat exchanger
p	pipeline

safety and healthy, but also systematically identifying and monitoring crucial environmental aspects through all levels of the food chain. On the other side, cleaning operations are crucial in many industrial sectors (e.g., food, pharmaceutical, and chemical industry) to obtain microbiologically safe products. In food processes, industrial cleaning is of great importance to ensure hygienic production conditions (Tanmay et al., 2014). All food processing equipment, lines, and utensil surfaces that come into contact with products must be thoroughly cleaned and sanitized before any subsequent production (Burfoot and Middelton, 2009). This stage of production process provides a quality product by elimination of cross contamination and microbial growth on production surfaces.

Cleaning process in CIP system is complex, where the efficiency depends on many factors, e.g., the soil to be removed, cleaning time, the temperature of the cleaning agent and the hydrodynamic effect of the moving liquid (Lelieveld et al., 2003; Piepiórka-Stepuk and Diakun, 2012). Realization of the cleaning process is associated with high energy consumption costs, and the purchase and neutralization of chemical cleaning agents (Struk-Sokołowska, 2011; Wojdalski and Dróżdż, 2012; Tanmay et al., 2014). As much as 13.5% of the total energy consumption in food production is associated with the cleaning of equipment using the CIP system (Piepiórka-Stepuk and Diakun, 2014). It usually depends on many factors, among which the basic ones are properties of raw materials, product requirements, technology, the size and structure of production, technical equipment, the degree of mechanization of production operations, processing capacity and organization of the production. For example, a milk plant is likely to use 13% of its energy on CIP, whereas a powdered milk, cheese and whey process is likely to use 9% of its energy on CIP (Jude and Lemaire, 2014). This stems from the need to heat and maintain a large volume of cleaning solutions, up to as high as 95 °C (Lelieveld et al., 2003; Wilson, 2003; Mercadé-Prieto et al., 2005; Tamime, 2008). Laboratory tests on cleaning the pipelines show that the energy consumption for heating up the cleaning solutions is as much as twelve times higher than the energy required for their flow rate (Diakun et al., 2012). The use of high-temperature cleaning solutions will activate a chemical reaction between sediments and cleaning agents (Blel et al., 2007; Almecija et al., 2009). This is helpful in the removal of fat, sugar and mineral deposits from surfaces, but the use of cleaning agents at too high temperatures has a negative effect on protein sediments. The temperature and types of chemical agents should depend on the type of sediment to be removed, the construction materials out of which the surfaces to be cleaned are made and the use of active substances contained in cleaning agents. Preheating cleaning solutions and chemical cleaning agents are the main components of the cost of cleaning and at the same time they are the factors which negatively impact on the environment (Lin et al., 1999; Grasshoff, 2002; Gönder et al., 2010). Therefore, it is reasonable to search for cleaning conditions that minimize energy consumption. This reduction can be reached through process optimization, which can also reduce other economic and environmental costs such as usage of cleaning agents.

Many authors who study the process of cleaning, optimize this process only in terms of cleaning quality (surface cleanliness), considering various factors of the process such as: flow velocity, temperature, concentration of chemicals and their impact on duration of cleaning. Their studies relate to various fouling and objects — we focused on this aspect during the literature review. Goode et al. (2010) optimized the time needed for the removal of yeast impurities compared to other cleaning agents. Kim et al. (2002) and Almecija et al. (2009) determined the quality of cleaning of microfiltration membranes. Blel et al. (2007) and Burfoot and Middelton (2009) analyzed the impact of flow conditions on the removal of micro-organisms from the surface. Most papers relate to the removal of milk fouling from the production surface, because post-production sediments occurring in food processing are the most difficult to remove. Gillham et al. (1999) found that removal of whey protein deposits from stainless steel pipes was strongly dependent on temperature. Some authors have reported optimal chemical concentrations that minimize cleaning time (Fryer et al., 2006; Jeurnink and Brinkman, 1994) and others theirs attention focused on mechanical impacts (Changani et al., 1997; Gillham et al., 2000).

This study aims to determine the optimal conditions for cleaning the pipes and plate heat exchangers in flow using the CIP method. Pure water without chemical agents was used as a flowing cleaning medium in the research. The study was conducted to increase the mechanical impact and minimize the consumption of cleaning agents. Items to be cleaned were contaminated with hot milk. Milk is a complex fluid with a number of thermally unstable components, with equally complex fouling behavior; therefore, this type of fouling is the subject of tests for many researchers who study about cleaning in CIP system (Jeurnink and Brinkman, 1994; Changani et al., 1997; Gillham et al., 2000; Fryer et al., 2006). Cleaning was carried out in a laboratory CIP station. A series of experimental tests were carried out, based on which the degree of cleanliness was evaluated and the energy consumed was measured. The variables of the cleaning process include: temperature and flow velocity of cleaning fluid (pure water), the amount of cleaning fluid and cleaning time. Based on the results obtained the regression functions of energy consumption and the quality of cleaning were determined. A multi-criterion function for two opposing optimization criteria was developed: minimization of the energy consumption and maximization of the degree of cleanliness. Non-dominated area of polyoptimal cleaning conditions defining the favorable effects of a cleaning fluid without the use of chemical agents was determined.

2. Materials and methods

Tests were conducted in a laboratory CIP station which consisted of two tanks with a capacity of 0.3 m^3, pumps, a system of pipes and valves (Fig. 1). One of the tanks (2) is a build-in heater with a capacity of 3 kW and thermal insulation. The heater is power by a thermostatic control system allowing the warming-up and stabilization of the liquid temperature in the tank (accuracy ±1.5 °C). This tank was used to prepare the cleaning liquids. Second tank (3)