FLOWING FOAM: AN ECO-EFFICIENT STRATEGY FOR CLEANING OF CONTAMINATED INDUSTRIAL EQUIPMENT

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ABSTRACT

In the food industry, cleaning contaminated surfaces requires the adoption of new cleaning strategies that can provide higher cleaning efficiency with minimal energy and water consumption. Cleaning using wet flow foam can represent an innovative method due to interesting foam mechanical properties e.g. generation of significant drag forces and chemical properties of the surfactant as a cleaning agent. This study compares the innovative cleaning process using flow foam (50% air/water and surfactant (0.15% w/w)) and standard cleaning-in-place treatment for cleaning 2B stainless steel soiled by droplets containing hydrophilic and hydrophobic *Bacillus* spores [*Bacillus subtilis* PY79] allowed to dry prior to cleaning to enhance adhesion forces. Among the spores, the hydrophobic *Bacillus* spores were more difficult to clean than the hydrophilic ones. Results suggested a synergy between the increase in shear stress and the reduction in bubble sizes, resulting in an improvement in the efficiency of cleaning by the fluid foam. Fluctuations of both liquid film thickness and local wall shear stress, and the capillary imbibition at the point of contact between the foam and spores could potentially explain the removal phenomenon. Compared to the standard CIP process, foam flow cleaning showed high efficiency and dramatically reduced water and energy expenditure by thirteen-fold and thirty-three-fold, respectively.

INTRODUCTION

In food industrial environments, surfaces have been reported to be contaminated by a range of microorganisms, including pathogenic and spoilage bacteria (F. Masotti et. [1]). Once introduced, many bacteria are able to persist on the contaminated surfaces or even grow if environmental conditions are suitable. The aerobic spore-forming *Bacillus* bacteria greatest impact on quality, food safety, and the economy due to their spoilage-causing capabilities and to a lesser extent, disease-causing potential and are well known to attach to any kind of surfaces and therefore food equipment (S. D. Bennett et al. [2]).

As stated in the literature cleaning operations in food industries require water, chemicals, and energy inducing significant environmental influence (S. Khan et al. [3]); however, almost little knowledge is known on the potencies produced by flowing foam in cleaning operations working with much less energy and water, producing considerably less wastewater (A. Al Saabi et al. [4], H. Dallagi et al. [5]). Foams show an unexpected and non-linear rheological behavior since it is influenced simultaneously by liquid and gas properties (H. Dallagi et al. [6], H. Dallagi et al. [7]). This difficulty has not prevented foams from being a major subject of active research given their intensive use in many industrial sectors, such as food industries, cosmetics, nuclear engineering, petroleum engineering, and firefight.

Primary works have shown that flowing foams can produce up to 2000 times higher wall shear rates than single-phase flow. Aqueous foams are complex fluids having original mechanical properties which rely on their low density and high surface area combined with their ability to elastic respond to lower stresses and to flow like a viscous liquid with large distortions (H. Dallagi et al. [8]). In previous work (A. Al Saabi et al. [4]), a study of cleaning with foam flow at different qualities (50%, 60%, and 70%) and velocities (2, 4, and 6 cm/s) was made. Results show that wetter foam can be more efficient to remove contamination than drier one. This experimental work will be a database to validate the efficiency of the thin liquid film generated by flowing foam in the cleaning of contaminated surfaces with *B. subtilis* spores from stainless steel

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surfaces. Therefore, the first part of this work presents a detailed characterization of these foam flow conditions which the aim was to understand the mechanism of the detachments using foam flow, identify key parameters, then test them on cleaning of stainless stainless-steel coupons contaminated by spores' droplets. More details are given in (H. Dallagi et al. [9]).

MATERIALS AND METHODS

Coupons and test pipes

Stainless steel coupons of 6.75 cm^2 (0.045 x 0.015) of 1mm width were designed to be inserted to cover one internal face of the square stainless steel pipes (figure 1).

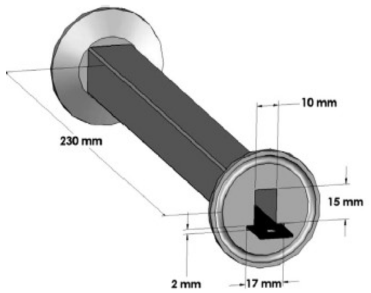

Fig. 1. Test pipes (Cunault et al., 2015)

For all the experiments, the used coupons were a hydrophilic material: the AISI 316 stainless steel with pickled (2B) finish coupons provided by APERAM, Isbergues, France) (Ra= 0.3*µm, θ_{water} = 66°). These coupons were not used directly for the cleaning experiments, but they were subjected to an aging protocol using milk (powder, 150g/l) and sodium hydroxide (0.5% ww) to stabilize their surface properties, which becomes relevant to the food processing equipment surfaces.

Surface soiling with *Bacillus* spores

The cleaning experiments were done to see their effect in detaching the spores of *Bacillus subtilis*. For this study, hydrophobic and hydrophilic spores of the *Bacillus subtilis* strain were used. The hydrophilic one is *B. subtilis* PY79 (Bs-PY79), a laboratory strain. The second one Bs-PY79 ΔspsA, a mutant of Bs-PY79, was produced in the lab by the removal of the gen spsA. This strain is less hydrophilic and negatively charged than spores of the PY79 strain (T. Dubois et al. [10]). As previously described (M. Deleplace et al. [11], C. Faille et al. [12]) after producing spores, 'MATH' tests were performed to evaluate its hydrophobic character.

1 µl of spores' suspension at 10^8 CFU/ml was prepared to soil the coupons as a deposited droplet. The surface load on the coupons was 5.10^5 CFU/coupon.

Foam cleaning in place

The experimental facility was designed to handle the different requirements of foam flow. Its geometry is capable of making studies for a horizontal foam flow under different velocities and foam structures. The experimental rig was designed according to (P. Tisné et al. [13]). Several physical measurements were performed to characterize the dynamic of foam and the bubbles' size such as polarography, conductometry, and image analysis. These measurements are necessary to understand the cleaning mechanisms and the improvement of their efficiency. Different conditions of wet flow foam (50% air/water and surfactant (0.15% w/w)) were chosen, by varying the shear stress and the size of the bubbles, in order to test the capacity of the foam to remove *Bacillus* spores from stainless steel surfaces.

RESULTS AND DISCUSSION

Foam characterization

Since we placed the contaminated coupons at the top part of the horizontal pipe, it is necessary to identify such an induced phenomenon.

The results of polarography and conductometry techniques show an instantaneous variation (in amplitude and frequency) which is strongly related to the passage of the bubble with different sizes (figure 2). As the velocity increase, the bubbles at the top wall of the pipe becomes smaller leading to a higher wall shear stress, higher frequency, and lower amplitude. The vibration of the bubbles and their rotation at the wall increase with the velocity. This kind of movement leads to a strong perturbation of the liquid film that will be in contact with the contamination.

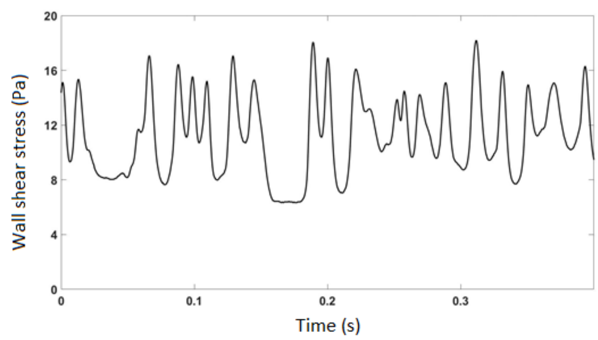

Fig. 2. Example of the fluctuation of the shear stress at the wall when foam flows.

Foam cleaning

A direct comparison between spores' kinetics removal for the different conditions of foam flow cleaning was carried out.

For both strains (hydrophilic and hydrophobic spores), foam cleaning at a higher flow rate

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(corresponding to a turbulent regime) appeared to be more efficient than the foam at a lower flow rate (corresponding to 1 D flow). Indeed, less remaining contamination in 20 min cleaning was observed when the foam flow like a block as a laminar flow, resulting in 2 and 1.2 log reduction for hydrophilic and hydrophobic strain respectively. As for the turbulent flow regime, the result achieved about 4 and 2 log reduction for hydrophilic and hydrophobic strain respectively. First, these results show that among the spores, the hydrophobic *Bacillus* spores were more difficult to clean than the hydrophobic ones, due to the presence of many clusters which are known to be very resistant to the cleaning process. Second, it highlights the importance of mechanical action (shear stress) to improve the cleaning efficiency of the spores from the surface.

When comparing two conditions of foam flow at the same shear stress but different bubble sizes, foam with a small bubble size was more efficient to clean hydrophilic spores. In fact, almost no residual contaminations were observed after 20 min of cleaning as shown in figure 3. In conclusion, a synergy between the increase in shear stress and the reduction in bubble sizes resulted in an improvement in the efficiency of cleaning by the foam. The phenomena observed such as the fluctuations of both liquid film thickness and local wall shear stress, and the capillary forces at the point of contact between the foam and spores could potentially explain the removal phenomenon.

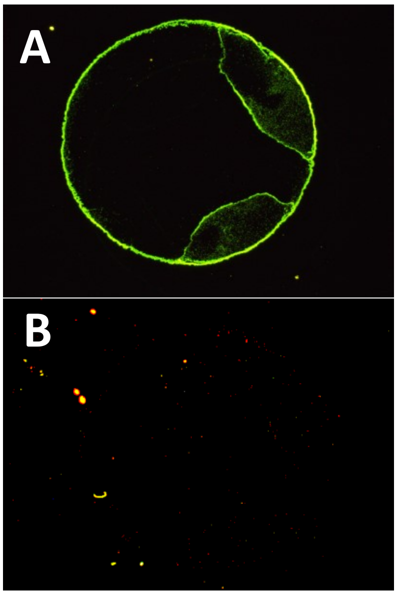

Fig. 3. Microscopic observations of the stainless-steel coupon contamination before cleaning and after 20 min using foam flow. A before cleaning, B after cleaning

The comparison of cleaning using foam flow and CIP at the same shear stress with identical temperature (at 20°c) and SDS concentration (0.15%.) showed that foam flow cleaning resulted in high efficiency with about 2 additional log reductions while reducing dramatically the water and energy expenditure.

CONCLUSION

Cleaning of *Bacillus* spores using wet foam flow gives promising results that suggest this method be an alternative cleaning process for the food industries. An adequate optimization of the process is required for the enhancement of the cleaning efficiency and to reduce water and energy consumption.

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