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An experimental comparison of film flow parameters and cleaning behaviour of falling liquid films for different tilt angles

Enrico Fuchs[a,*], *André Boye*[b], *Roman Murcek*[b], *Jens-Peter Majschak*[a,b]

[a] *Technische Universität Dresden, Faculty of Mechanical Engineering, Institute of Processing Machines and Mobile Machines, 01062 Dresden, Germany*
[b] *The Fraunhofer IVV, Branch Lab for Processing Machinery and Packaging Technology Dresden, Heidelberger Str. 20, 01189 Dresden, Germany*

ABSTRACT

Efficient cleaning is crucial in the food industry due to increasing safety needs, cost pressure and diminishing size of production batches. In Cleaning in Place (CIP) systems different flow types provide the cleaning effect by interaction, wherein falling liquid films make a significant contribution to cleaning. The flow of falling films can be significantly influenced by the design of the surface and, for example, of the tilt angle. In a previous publication it was shown for a low tilt angle of 30° that for resource efficient cleaning a low wetting rate is suitable. It was pointed out that mean wall shear stress and mean flow velocity have an influence on the cleaning progress. In this paper the investigations are extended to describe the influence of the surface inclination in the range of 30–90° on the flow and cleaning behavior of zinc sulfide/Xanthan gum soil layers on stainless steel for film Reynolds numbers of 1190-3110. The results show that the tilt angle has a major impact on the film thickness, wall shear stress and the mean cleaning rate. Cleaning results for three different stainless steel surfaces show that a low surface roughness does not necessarily lead to a better cleaning result.

Keywords: Falling liquid film; Falling film cleaning; Film thickness; Wall shear stress; Velocity; Stainless steel; Cleaning efficiency; Cleaning performance indicator

1. Introduction

When it comes to food production, there are different requirements from both consumers' and producers' perspectives. The manufacturer wants to minimize resource-input, thus minimizing the cost. However, the manufacturing of contamination-free and safe products has the highest priority in the food processing industry. This is also required by law (e.g. Machinery Directive 2006/42/EC). Therefore, food processing machines are increasingly delivered with automated cleaning systems. For open equipment and tanks, static and dynamic cleaning systems are installed, which produce, among other things, liquid falling films. These films flow in areas not reached by impinging jets or sprays, and provide the main cleaning effect. Areas that can be reached only by liquid films are usually more difficult to clean. Due to the lower mechanical action of falling liquid films, compared to jet cleaning, they have a limiting effect on CIP processes in terms of cleaning time and cleaning fluid consumption. Therefore, to guarantee good cleaning, usually a large amount of cleaning fluid, and consequently energy, is needed.

Previous experimental studies on falling films have shown that the fluid consumption based cleaning performance indicator can be increased by using a low volumetric wetting

* Corresponding author at: Technische Universität Dresden, Faculty of Mechanical Science and Engineering, Institute of Processing Machines and Mobile Machinery, 01062 Dresden, Germany. Tel.: +49 351 463 37850.
E-mail address: enrico.fuchs@tu-dresden.de (E. Fuchs).
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Nomenclature

Latin symbols

B	wetted width, m
$E_{V/W}$	fluid consumption based cleaning performance indicator, mg cm^{-2} s^{-1} per m^3 s^{-1} m^{-1}
F	reduction factor, dimensionless
g	gravity, m s^{-2}
Ka	Kapitza number, dimensionless
$\bar{R}_{95}$	mean cleaning rate, mg cm^{-2} s^{-1}
Re	film Reynolds number, dimensionless Initial mean surface mass, mg cm^{-2}
S_a	roughness, site-specific, arithmetic average, µm
S_z	roughness, site-specific, mean depth, µm
$\bar{t}_{95}$	mean cleaning time, s
$\dot{V}$	volume flow rate, m^3 h^{-1}
$\bar{w}$	mean velocity, m s^{-1}

Greek symbols

α_{Pl}	inclination of the substrate,°
$\bar{\delta}$	film thickness, mm
δ_m^+	mean dimensionless film thickness
δ_{max}	maximum film thickness, mm
δ_{min}	minimum film thickness, mm
$\delta_{m,Nu}^+$	mean dimensionless film thickness of Nusselt
δ_{Nu}	Nusselt film thickness, mm
$\bar{\delta}_{sd+}$	mean film thickness plus standard deviation, mm
$\bar{\delta}_{sd-}$	mean film thickness minus standard deviation, mm
ϑ	temperature, °C
λ	excitation wavelength, nm
ρ	density, kg m^{-3}
τ_W	wall shear stress, Pa
η	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
Γ_v	volumetric wetting rate, m^3 h^{-1} m^{-1}
Γ	mass flow rate per wetted width, kg h^{-1} m^{-1}

rate (Fuchs et al., 2013). In addition, a relationship between fluid mechanical parameters (wall shear stress, velocity) and cleaning behavior could be established. These results were obtained for a tilt angle of 30°. Other publications were able to demonstrate an optimum angle of inclination for the efficient removal of deposits based on experimental data for 67° (Lerch et al., 2013) or 90° (Patel and Jordan, 1970). Based on a previous publication (Fuchs et al., 2013) in this paper the cleaning effect of falling liquid films in combination with a food model soil is investigated for different tilt angles and film Reynolds numbers. Furthermore, the cleaning results are compared with flow parameters, e.g. film thickness, velocity and wall shear stress.

2. Experimental techniques and methods

The test rig and the measurement methods are described in detail in a previous publication (Fuchs et al., 2013). Therefore only a brief summary will be given here. All experiments were done with a gravity driven falling liquid film. The test rig consisted of a pump unit, flow meter and measuring area installed in an enclosure, in order to avoid factors like disturbing light (see Fig. 1). A heating device provided a constant liquid temperature of ~25 °C for all experiments. The cleaning fluid is spread by a spray lance (inner diameter: 16 mm, length: 100 mm; 12 equally spaced holes, diameter: 2 mm). This is followed by a 500 mm long inlet area to ensure reproducible flow conditions with less influence of the liquid distribution device. Afterwards the measuring area with a length of 300 mm for the different stainless steel samples was arranged.

2.1. *Cleaning studies*

A phosphorescence method was used for measuring the progress of cleaning of a dried layer of Xanthan gum suspension, whereby the cleaning process can be temporally detected and spatially resolved by an optical measurement system. This method was first introduced by Schöler et al. (2009). The food model soil was 0.8 g Xanthan gum and 3 g zinc-sulfide crystals as tracer mixed with 1 L deionised water. Xanthan gum is a thickener for many products in the food and pharmaceutical industry. It is an ingredient in, for example, ketchup, soups and cosmetic products like vanishing cream. Additionally, many products contain particulate components (e.g. cosmetic products). Therefore, the model soil covers a reasonable amount of realistic deposits in machinery or facilities. For the soiling of the stainless steel samples (dimension 300 mm × 100 mm) a dip coating process was used (see Fuchs et al., 2013). To determine the influence of the surface structure on cleaning behaviour, different stainless steel samples were tested (EN 1.4435 bright finish, EN 1.4435 electro-polished and EN 1.4404 sanded). The cleaning tests were done using deionised water for three different tilt angles against the horizontal (30°, 60°, 90°; Fig. 1).

To describe the stainless steel surface properties, the static contact angle as a reference value for the surface tension and the roughness were measured (see Table 1). The static contact was determined by a drop shape analyzer DAS-10 (Krüss). Two repetitions were done for every sample (fluid: deionised water, temperature: 20 °C, drop volume: 20 µl, 20 s between drop placement and measurement). In addition, the measurement of the surface roughness was carried out using high-resolution scandisk confocal microscopy (µsurf explorer, NanoFocus AG). The roughness parameter S_a is the arithmetic mean value of the absolute ordinate values and S_z is the mean roughness depth within the measuring area (260 µm × 260 µm).

To compare the cleaning results, the mean cleaning rate reported by Mauermann et al. (2010) is used:

$$\bar{R}_{95} = \frac{0.95 \cdot \bar{m}_0}{\bar{t}_{95}} \quad (1)$$

The mean cleaning rate, $\bar{R}_{95}$, represents the relation between mean cleaned surface mass $\bar{m}_0$ and the time, $\bar{t}_{95}$, at which 95% of the initial soil is removed. The higher the cleaning rate the faster the soil is removed. Therefore, it is an indicator for time efficient cleaning.

2.2. *Film thickness*

The film thickness was determined by a fluorescence method which is described in detail in Fuchs et al. (2013). UV-lamps illuminate the tracer (Esculin with a concentration of 0.02 g/L) dissolved in water. The tracer emits light which is detected by an optical measuring device. The dependency between the