

INFLUENCE OF THE FILM FLOW CHARACTERISTIC ON THE CLEANING BEHAVIOUR

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ABSTRACT

The cleaning of machinery and facilities is a key process to meet the safety needs in food and pharmaceutical production. The high significance of cleaning is a reaction to the rising importance of environmental protection. Due to the mostly unknown interaction between process parameters and cleaning behaviour of deposits, too many resources are used in industrial cleaning steps. This results in growing costs for the cleaning processes.

This publication presents results of laboratory scale cleaning investigations of falling films with respect to the influence of the film thickness and hence predictable parameters. A fluorescence method was applied for determination of film thickness on stainless steel samples. With this publication it can be shown that a connection exists between the falling film cleaning behaviour and the wall shear stress or the mean velocity. Additionally it is shown that a low wetting rate is the most effective setup for saving cleaning fluid.

INTRODUCTION

Contamination free and safe consumer products are given highest priority in the food and pharmaceutical industry. Therefore meeting the requirement of consistently high product quality cleaning is a key step. Validated and mainly automatic cleaning-in-place (CIP) processes are used, however currently resource efficiency is becoming increasingly important, particularly targeting the reduction of cleaning costs and down time including consideration of environmental aspects. Environmental conservation is also demanded by an EU directive 2008/1/EG. The contradictory intentions of saving resources and producing safe consumer products, necessitates the fulfilment of a balancing act for the food and pharmaceutical industry. A better understanding of influences on cleaning, especially of the flow parameter, can provide a contribution to reach resource-efficient processes.

For CIP-processes static or dynamic cleaning devices are

used. Using a spray ball or a rotating head, the main mechanical cleaning effect is provided by the gravity-driven falling film. Patel and Jordan (1970) investigated cleaning for the first time under the application of falling film. They used microorganisms to assess the influence of tilt angle between 30 ° and 150 ° (relating to the horizontal) on cleaning results. They identified that a vertical substrate (90 °) leads to the best cleaning results. Additionally, they determined a higher cleaning efficiency with increasing flow rate, caused by intensified turbulence and higher mechanical scrubbing. In addition, Patel and Jordan (1970) supposed an intensified turbulence caused by eddies and roll waves on the film surface, as an explanation for better cleaning. Lerch et al. (2013) studied washing-in-place processes (WIP) by falling film. In cleaning studies they compared a particulate riboflavin test soil in dry, pre-wetted and wet conditions. These experiments concluded that a tilt angle of 67 ° leads to faster cleaning than a vertical position describing it with a constant diffusion coefficient. The coefficient is independent of the tilt angle but, with diminishing inclination of the plane, the film thickness and the concentration gradient of the rinsing film increases. The best cleaning results were obtained with a combination of pre-wetting of dried soil, inclination of the sample and a high flow rate. Finally, a general relationship for all WIP processes could not be given, thus additional studies of flow parameters influencing cleaning behaviour and cleanability of material, as well as surface finishes, should be conducted. In addition, the different experimental results of Lerch et al. (2013) and Patel and Jordan (1970) indicate that the acting cleaning mechanisms may also have an influence on the design of components. Therefore it is necessary to do further cleaning studies with different soils in order to obtain general statements.

Wall shear stress is commonly used as a description of cleaning (e.g. Detry et al. 2009), which can be calculated through knowledge of film thickness (Brauer 1971).

Resultantly, it is possible to quantify the influence of film thickness and waviness of the film surface on cleaning.

Numerous methods were used to measure the local film thickness. Optical systems allow a spatially and temporally resolved measurement without influencing the falling film. This method is based on fluorescence technique, first introduced by Hewitt et al. (1964) and Hiby (1968). It was used, for example, by Adomeit (1996) to investigate the wave structure of Dimethylsulfoxid film flow on the inner side of a transparent vertical pipe. In measuring the intensity of the fluorescence of the film forming fluid it is possible to calculate the 3-dimensional film thickness. Al-Sibai (2004) used Cumarin 152a, mixed with silicone oil and a laser light to excite fluorescence. Ausner (2006) also used the light-induced-fluorescence (LIF) technique to measure two fluids (water and Toluol) separately and in parallel on smooth and structured stainless steel plates. Whereas Hoffmann et al. (2005) used this experimental data to validate his CFD (Computational Fluid Dynamics) calculations. A fluorescence tracer Rhodamin B was used for the water phase and 1-(4'-Nitrophenyl)-6-Phenyl-Hexa-1,3,5-triene for the Toluol solution. In addition Vlachogiannis and Bontozoglou (2001) used this technique to determine the wave dynamics with the tracer Fluorescein. For film thickness calibration different methods e.g. cuvettes, contact needle and weighted Petri dishes were used.

This paper shows (a) the local film thickness and its predictable flow parameters for different wetting rates in comparison with cleaning results provided by falling film on surfaces with only 30° inclination. The film thickness was predicted by a modified LIF technique that uses a non-toxic tracer with very high fluorescence intensity even at low concentration. Several steps of correction are minimising various errors and lead to high quality measurement data. The paper comprises a droplet calibration method, which allows the consideration of different optical properties of the probes. Furthermore (b) new results for cleaning a food based model soil by gravity driven falling film are presented based on the discrete cleaning rate. Finally this paper presents (c) a comparison of film flow parameters and cleaning results.

EXPERIMENTAL TECHNIQUES

The test rig used for the cleaning experiments is shown in Fig. 1. 200 litres of cleaning fluid (distilled water) are stored in a tank and pumped into an intermediate container. An overflow guarantees a constant fluid level. Hence as the flow is not influenced by a pump, a constant pressure at the outlet is ensured and so an undisturbed film formation can be assumed. An electric heating element guarantees that all experiments are done with a temperature of ~25 °C. The flow meter is positioned between the tank and the outlet. With an additional valve, it is possible to set a flow rate between 22.8 l/h and 236 l/h.

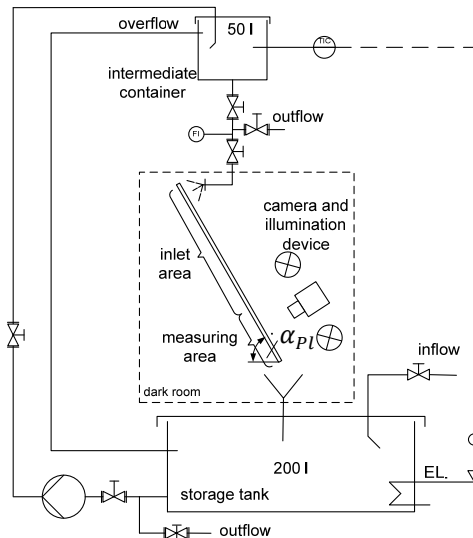


Fig. 1 Cleaning and flow measurement test rig

In relation to the 100 mm wide stainless steel substrates (EN 1.4435, AISI-316L), a volumetric wetting rate

$$\Gamma_v = \frac{\dot{V}}{B} \quad (1)$$

from $0.23 \text{ m}^3/(\text{h} \cdot \text{m})$ to $2.36 \text{ m}^3/(\text{h} \cdot \text{m})$ is possible. To assure a fully developed film flow, an inlet area with a length of 500 mm is used. Takamasa and Hazuku (2000) noted that for wave formation on a vertical surface the entry length of $L = 333.5 \text{ mm}$ is necessary for a completely developed flow. An inlet area of ~500 mm used in the test rig is sufficient to ensure a developed film flow; this has been verified for each setting. Afterwards the measuring area, with a length of 300 mm, was arranged. Optical measurements are achieved by utilising a camera and an illumination device above the measuring area.

METHODS

Soiling preparation

The model soil consists of distilled water merged with 0.8 % (w/v) Xanthan (CAS 11138-66-2) and 3 % (w/v) zinc-sulfid crystals (Co. Honeywell® 50018 Lumilux®), added as a tracer to increase the contrast between surface and soil. The solution was mixed for 30 minutes with a rotating speed of 700 r/min until all Xanthan was dissolved.

Soiling process

A dip coating process was used for soiling, which ensured a reproducible coating of the substrates. For this probes with dimensions of 300 mm x 100 mm were dipped in a container filled with the model soil. A constant dip velocity of 5 mm/s and return stroke velocity of 2 mm/s was applied. This slow dip velocity avoided the insertion of air bubbles, whilst the slow return stroke velocity ensured the draining of any excess amount of soil.

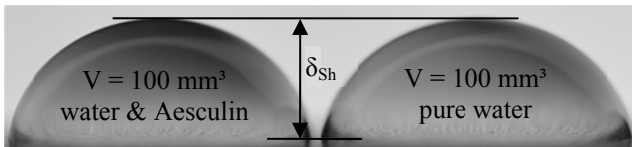


Fig. 2 Shadow method to determine the droplet height

Experiments have shown that soil with higher viscosity and a slow return stroke velocity result in a smooth and reproducible soil layer. Following the soiling process, the substrates were dried for 24 hours in normal climatic conditions (23 °C, 50 % humidity). The test samples for calibration were prepared with different surface masses with the apparatus described in Mauermann et al. (2010a). The applied soil mass was determined by differential weighting.

Film thickness

In order to choose a suitable tracer for the film thickness measurements, Riboflavin, Aesculin and Fluorescein were compared. Aesculin dissolved in water with a concentration of 0.02 g/l (w/v) showed the same fluorescence intensity as Fluorescein with a concentration of 0.1 g/l and a much higher intensity in contrast to Riboflavin (0.1 g/l). Aesculin was chosen for its property of high fluorescence intensity at low concentration. Therefore the likelihood of the fluorescent indicators influencing the fluid flow is lower. Thus it can be assumed that there is only a small influence of the tracer on relevant medium properties e.g. viscosity. The fluorescence was excited by 2 ultraviolet lamps placed above, causing the water – Aesculin solution to emit light. A band pass filter positioned in front of the camera system avoids disturbing light. After that the camera takes an image with an exposure time of 1ms.

Using the shadow measurement technique to examine the droplet height, it was demonstrated that Aesculin, in comparison with pure water, does not change the properties at the solid – liquid and liquid - atmosphere interfaces compared with pure water (Fig. 2). Hence a similarity of flow properties of pure water and water mixed with Aesculin can be assumed.

To calibrate the film thickness in dependence of measured fluorescence intensity a droplet calibration process was used, which was tested in a similar manner to that used in Schulz and Schmidt (2012). Attempts with a Petri dish showed that a higher thickness is necessary for complete wetting, therefore it was not possible to calibrate low film thickness. Additionally, using drop calibration, it is possible to consider the change of optical surface properties of the samples. The same solution was used for the calibration process as well as film thickness measurement; serving to eliminate errors by weighting, mixing and changing fluorescence intensity through pH-Value. To determine the droplet height two approaches were used to measure the maximum thickness in the middle of a droplet. The droplets were dosed with a precise pipette and the mean radius $\bar{r}$ of the droplet was measured with a camera from above. To calculate the droplet height, the droplet shape can be approximated by a ball cut (Ausner 2006). It should be

noted that by using the ball cut approach, the general contact angle range must be known. The equation for calculating the maximum height of a droplet with a contact angle below 90° is:

$$\delta_d = \left(\sqrt{\frac{9V^2}{\pi^2} + \bar{R}^6} + \frac{3V}{\pi} \right)^{1/3} - \frac{\bar{R}^2}{\left(\sqrt{\frac{9V^2}{\pi^2} + \bar{R}^6} + \frac{3V}{\pi} \right)^{1/3}} \quad (2)$$

Additionally, the shadow method from beside the droplet was used to validate the droplet height (see Fig. 2). A good agreement between droplet calibration and shadow method can be shown. From a film thickness of approximately 2 mm the droplet contour shows an elliptical shape, which leads to the nonlinear gain in Fig. 3. At higher film thicknesses the droplet height was corrected with the following empirical equation, as determined by measurements with the shadow method:

$$\delta_{d,corr} = \delta_d - 0.0081 \cdot \delta_d^{3.248} \quad (3)$$

In Fig. 4 the relationship between corrected and measured droplet height with the confidence band of 95% (grey dashed line) is shown. To avoid failure of weighting of, for example, Aesculin or changing optical properties of surfaces, the authors recommend this calibration with every set up.

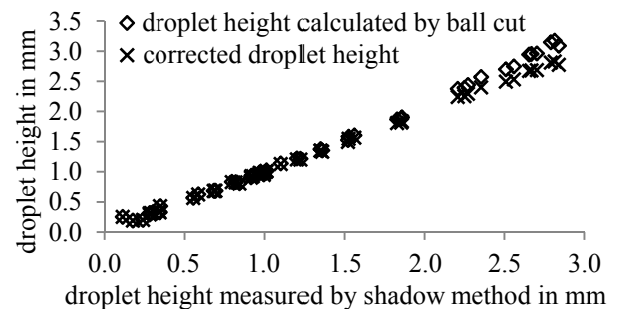


Fig. 3 Comparison of droplet shape and shadow method

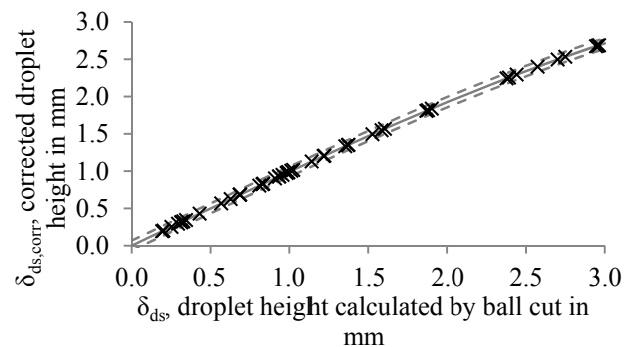


Fig. 4: Comparison between calculated and corrected droplet height with 95 % confidence band for the regression of the droplet height

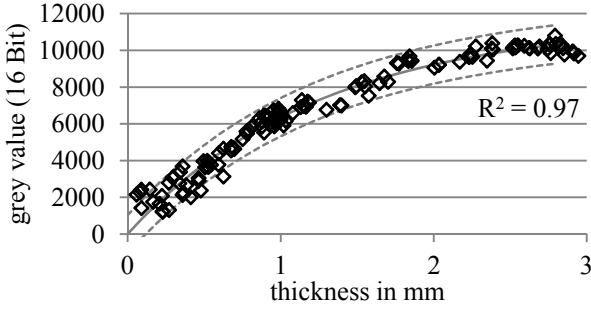


Fig. 5 Calibration curve for film thickness with 95 % confidence interval

Equation 2 and 3 can be used to determine the actual maximum droplet height as a function of droplet volume. Consequently the parallel measurement using shadow method can be omitted. The relationship between film thickness and grey values measured with the camera system is shown in Fig. 5; a weakening of the intensity of the penetrating fluids can be observed, which occurs as a result of the Beer-Lambert law (Beer 1852, Lambert 1760). Through application of a regression, the following equation (see Adomeit 1996) can be determined

$$I_C(\delta) = I_{C,max}(1 - e^{-k\delta}) \quad (4)$$

where $I_{C,max} = 11550$ and $k = 0.8002 \cdot 1/\text{mm}$. This equation is only valid up to a maximum film thickness of 2.8 mm; above this level the grey value does not change. In order to eliminate measuring errors, such as distortion of the camera system, some calculation steps are done. The processing of the data is described in more detail in Fuchs et al. (2012). During experiments a maximum difference of the local illumination intensity of 20 % was observed, which would lead to an error of the local film thickness of ~40 %. This deviation can be reduced significantly by measuring illumination distribution; this is not adequately considered in other studies. For example by using the following Look-up Table (LUT) (Dinstein et al. 1984)

$$I_{LUT} = I_{Ref,max}/I_{Ref} \quad (5)$$

and subsequent correction by matrix algebra

$$I_{i,2} = I_{i,1} \cdot I_{LUT} \quad (6)$$

The application of the LUT is possible, because a linear dependency of the UV-intensity with the extinction exists (see Fig. 6).

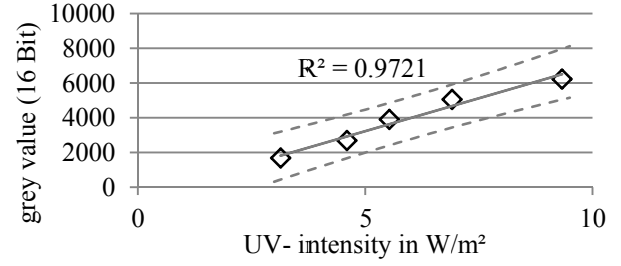


Fig. 6 Dependency of the measured emission and the illumination of a static film with 95 % confidence band

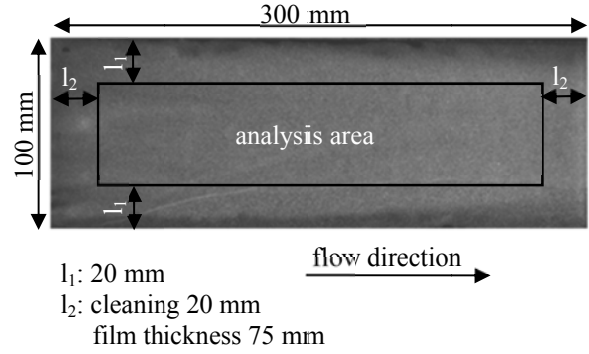


Fig. 7 Sample with area of analysis

For the correction, the distribution of the UV-intensity was measured with a sensor in 50 mm steps (Co. Ahlborn, FLA 623-UVA). By using a regression, a correction plane ($R^2 = 0.9946$) can be determined:

$$I(x,y) = 5.799 \frac{W}{m^2} \cdot \sin\left(\pi \frac{x-337.8}{809.7}\right) \cdot \sin\left(\pi \frac{y-316.1}{626.1}\right) \quad (7)$$

Therefore the illumination is calculated and the LUT can be considered for every pixel. The calculation of the film thickness was done by conversion of equation (4) for individual pixels, which creates a time resolved 3-dimensional interface. The considered area for film thickness is shown in Fig. 7.

Film thickness measurements are done for volumetric wetting rates between $0.46 \text{ m}^3/(\text{h} \cdot \text{m})$ and $2.36 \text{ m}^3/(\text{h} \cdot \text{m})$. The temperature of the fluid was ~25 °C.

Cleaning

New measurement techniques for the detection of soil deposits are described in Schöler et al. (2011) for pipe cleaning and Mauermann et al. (2010b) for spray cleaning in open systems. These techniques are the basis for intensive investigation of cleaning processes. In enabling a spatially and temporally resolved measurement, a closer look into cleaning processes of falling film is possible. For this purpose the phosphorescence method proved particularly suitable. The model soil was excited with LED day light for 6 s. After a short break of 0.5 s the image acquisition was taken with a camera exposure time (Co. Matrix Vision, mvBlueCougar-X125aG) of 2 s. The cycle of soil illumination and image acquisition was repeated every 10 s. Selection of the appropriate devices (see also Fig. 8) and setting is explained in Fuchs et al. (2012).

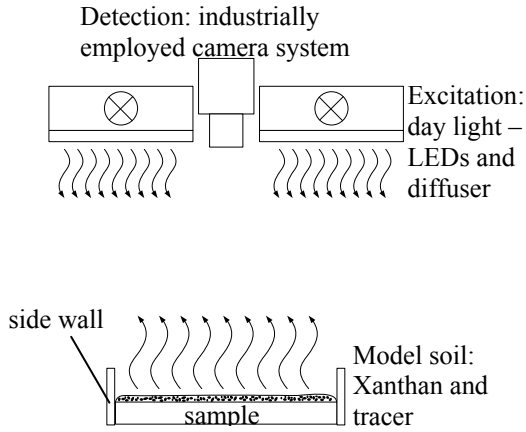


Fig. 8 Experimental setup for cleaning tests

The cleaning tests were done for a tilt angle of 30° with 4 repetitions for each measuring point. Four volume flow rates were used (93 l/h, 140 l/h, 192 l/h and 236 l/h). Related to the wetted width of the sample ($B = 0.1$ m), volumetric wetting rates in the range of $0.93 \text{ m}^3/(\text{h} \cdot \text{m})$ to $2.36 \text{ m}^3/(\text{h} \cdot \text{m})$ were applied. The upper threshold $1.86 \dots 2.24 \text{ m}^3/(\text{h} \cdot \text{m})$ was chosen based on recommendation of The American Society of Mechanical Engineers (2008). The cleaning was carried out under a temperature of $\sim 25^\circ\text{C}$, which guarantees comparable temperature conditions to film thickness measurements. Especially in the cleaning investigation, wetting problems occurred with wetting rates below a volumetric wetting rate of $0.93 \text{ m}^3/(\text{h} \cdot \text{m})$.

Data processing/Data analysis

The processing of the measurement data was also conducted as described in Fuchs et al. (2012). Thus errors through experimental setup and measurement were minimized. Additionally, differential illumination of the soil is taken into account; this allowed the relationship between excitation, emission and surface mass to be determined (see Fig. 9). The excitation was measured with an irradiation intensity measurement device (Co. Ahlborn, FLA 603 RW4) combined with a filter (Co. Asahi, ZVS0490).

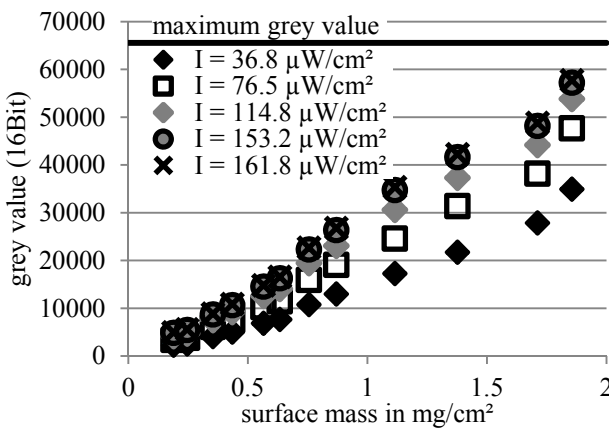


Fig. 9 Mean grey value in dependence of surface mass for different excitation settings

Through using a surface regression for the results shown in Fig. 9, the following equation can be determined ($R^2 = 0.9953$):

$$I_c(m, E) = (a \cdot m^2 + b \cdot m) \cdot (c \cdot E^2 + d \cdot E + e) \quad (8)$$

Due to the non-linear relationship between the measured intensity and the surface mass, the correction of the irradiation is done for every pixel separately. The calculation of the surface mass from the measured grey value is possible using:

$$m = -\frac{b}{2 \cdot a} + \sqrt{\left(\frac{b}{2 \cdot a}\right)^2 + \frac{I_c}{a(c \cdot E^2 + d \cdot E + e)}} \quad (9)$$

After this step, the mean surface mass $\bar{m}$ was calculated for the middle zone of the substrate (see Fig. 7). The changing grey value between dry state and first wetting is corrected by a factor; thus optical damping of the emission by the film is considered.

Based on Mauermann et al. (2010a) and Köhler et al. (2011) a normalized cleaning curve can be calculated by using:

$$r(t) = \frac{\bar{m}(t) - \bar{m}_{\min}}{\bar{m}_{\max} - \bar{m}_{\min}} \quad (10)$$

The following data analysis steps are described in Köhler et al. (2011) for a starch based model soil. For determining the cleaning characteristics the following Weibull model proposed by Dürr and Graßhoff (1999) was used:

$$r(t) = e^{\left(\frac{t}{t_c}\right)^{r_c}} \quad (11)$$

Next the cleaning time for reaching a residual deposit of 5 % from the initial surface mass $\bar{m}_0$ can be calculated with:

$$t_{95} = t_c (-\ln 0.05)^{\frac{1}{r_c}} \quad (12)$$

To compare cleaning results, a main cleaning rate as depicted below (also see Mauermann et al. 2010a),

$$\bar{R}_{95} = \frac{0.95 \cdot \bar{m}_0}{t_{95}} \quad (13)$$

defined as removed amount of soil per time, can be used. With this characteristic value it is possible to describe the time variation of the residual contamination independently from the surface mass.

RESULTS AND DISCUSSION

The structure of film boundary surface changes between lower and higher Reynolds numbers is shown in Fig. 10.

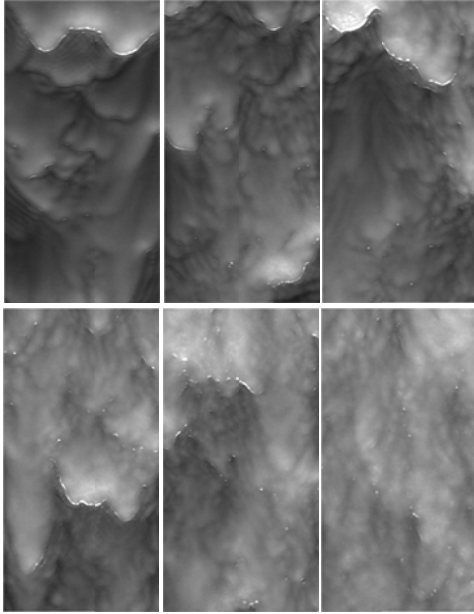


Fig. 10 Flow structure (from top left to bottom right Re = 143, Re = 290, Re = 366, Re = 437, Re = 598, Re = 734)

To compare different flow conditions the dimensionless Reynolds number, which can be calculated (Brauer 1971, Reynolds 1883) as shown below, was used.

$$Re = \frac{\bar{w} \cdot \delta}{\nu} = \frac{\dot{V}}{B \cdot \nu} \quad (14)$$

For a low Reynolds number of about Re = 143 single large waves were observed, but above Re = 366 the wave structure varied. The number of waves increases with increasing wetting rate and with a Reynolds number of 734 single large waves were no longer observable. Thus it can be confirmed, that with increasing Reynolds number, the waviness of the film boundary surface also increases. However, the difference between the maximum film thickness and the average film thickness seems to drop (see also Fig. 13).

To eliminate the influence of the fluid properties and the tilt angle of the substrates, a dimensionless film thickness can be used (Al-Sibai 2004):

$$\delta^+ = \delta \cdot \left(\frac{g \cdot \sin \alpha_{Pl}}{\nu^2} \right)^{1/3} \quad (15)$$

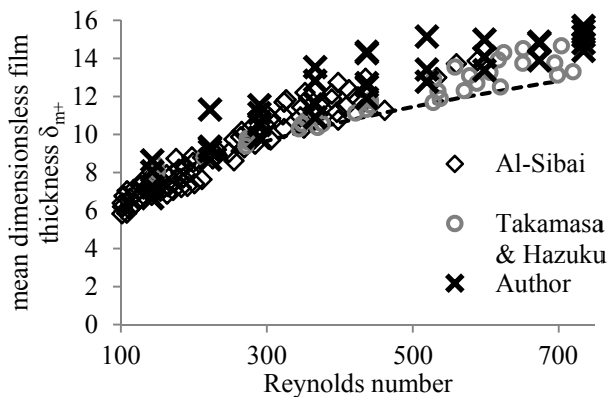


Fig. 11 Comparison of dimensionless film thickness

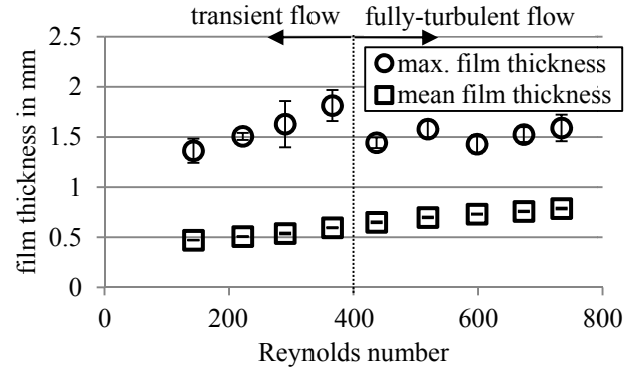


Fig. 12 Film thickness for a tilt angle of 30 °, bars represent standard deviation

In Fig. 11 the comparison of different authors shows a good agreement between the different measurements of the dimensionless mean film thickness. Especially compared to Al-Sibai (2004) and Takamasa and Hazuku (2000), the film thickness measurement shows a good correlation. However this is in contrast with measurements of Nusselt (1916) where the dimensionless film thickness is lower. Nusselt established a relationship between film thickness and Reynolds number, which is valid for a smooth laminar film, although this condition is given only for low Reynolds numbers.

A summary of the determined mean and maximum film thickness for different Reynolds numbers is shown in Fig. 12 for 9 repetitions per wetting rate. It is derivable that below a Reynolds number of Re = 400 the maximum film height increases with Reynolds number and for Re > 400 the maximum film thickness varies only slightly. In contrast to Ambrosini et al. (2002), there is no detectable general increase of the maximum film thickness with increasing Reynolds number. The decrease of maximum film height between Re = 366 and Re = 437 is caused by the wave form. The shape of the waves on the boundary surface changes from individual high waves to numerous waves (see also Fig. 10). From the mean film thickness a mean wall shear stress can be calculated. As the gradient of the velocity at the wall for turbulent flow is (nearly) similar to that of laminar flow, the wall shear stress can be calculated with the adoption of a square flow profile using (Brauer 1971):

$$\tau_w = \sin \alpha_{Pl} \cdot g \cdot \rho \cdot \delta. \quad (16)$$

Thus it can be concluded, that for low Reynolds numbers Re < 400, the variation of the wall shear stress is greater than for Reynolds numbers Re > 400. Likewise, from the film thickness, an average flow velocity can be determined:

$$\bar{w} = \frac{\dot{V}}{A} = \frac{\dot{V}}{\delta \cdot B} \quad (17)$$

In Fig. 13 the calculated mean wall shear stress and the mean flow velocity for a tilt angle of 30 ° is shown.

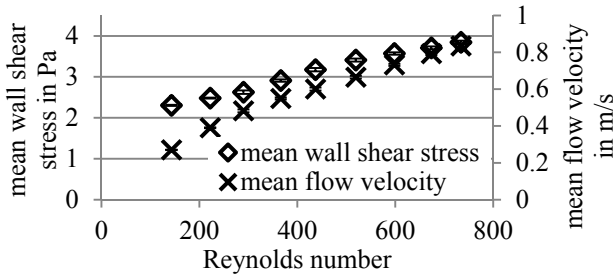


Fig. 13 Mean wall shear stress and mean flow velocity for tilt angle of 30°

With increasing volumetric wetting rate, the mean wall shear stress and the mean velocity increases nearly linearly. The flow velocity increases faster than the mean wall shear stress (see Fig. 13). One explanation is the flow profile, in which the gradient at the wall does not change as fast as the increasing mean flow velocity.

In the following section the measurement of the film thickness is compared with the cleaning tests. Typical cleaning curves of Xanthan soil are shown in Fig. 14. The residual contamination normalized to the initial surface mass as a function of time is also illustrated. For the presented experiments a clean surface is defined by a residual contamination of 5 % (horizontal line in Fig. 14). The cleaning process with the given set up shows four cleaning phases (see Fig. 15). In phase I there is no significant cleaning progress because swelling of the soil must first take place in order to minimize cohesive and adhesive forces. The three following phases are described in Bode et al. (2007) for whey protein. In phase II the cleaning rate increases with the progress of swelling, so the diffusion process dominates because the deposit swells in layers. In phase III the swollen soil is gradually carried away by mechanical force of the falling film, demonstrating a combination of dissolving and removing of the deposit by shear action due to cohesive and adhesive loss. In contrast to Bode et al. (2007), diffusion is apparently not the dominant process in this phase due to the inconstant cleaning rate. In the case of diffusion, the cleaning rate would be approximately the same as the result of a nearly constant concentration gradient. After phase III the cleaning rate decreases as the loss of adhesion force between material surface and model soil dominates, and hence cleaned area is increasing. In this section the Xanthan model soil is mainly removed by shear action of the flowing fluid.

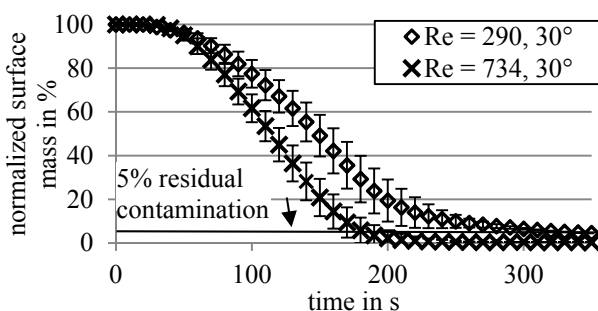


Fig. 14 Cleaning curves for different Reynolds numbers, bars represent standard deviation

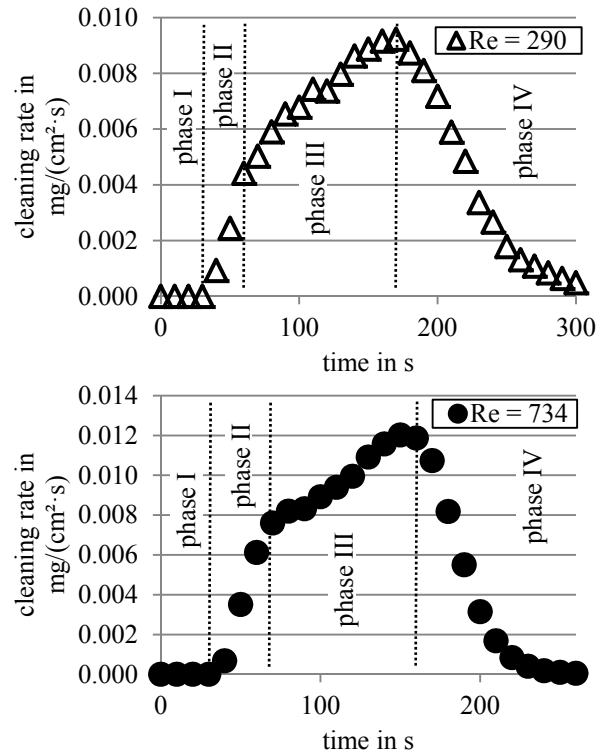


Fig. 15 Discrete cleaning rate for $Re = 290$ and 734 , tilt angle 30°

It is possible to calculate a mean cleaning time for all probes of a wetting rate set up until the defined boundary condition is reached. For the lowest wetting rate, the highest cleaning time is necessary. Vice versa; the highest wetting rate requires the lowest cleaning time. However the mean cleaning time depends on the initial surface mass, which makes another characteristic value necessary for comparison.

For every cleaning experiment a main cleaning rate can be calculated, which is independent from the surface mass until a residual contamination of 5 % related to starting soiling weight. A summary of the main cleaning rates with falling film on stainless steel is shown in Fig. 16.

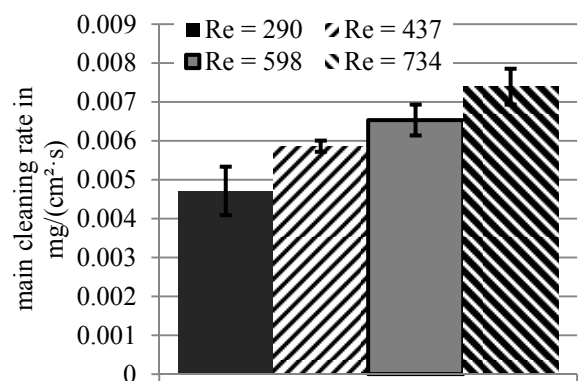


Fig. 16 Main cleaning rates for cleaning with gravity driven falling film until a residual contamination of 5 %, bars represent standard deviation

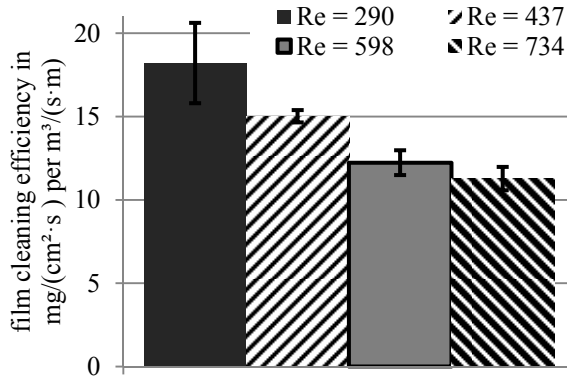


Fig. 17 Fluid mechanical cleaning efficiency for different Reynolds numbers, bars represent standard deviation

The influence of the wetting rate shows a good agreement to investigations of Lerch et al. (2013) where a high flow rate leads to faster cleaning. The main cleaning rate shows a dependency on Reynolds number. Within comparisons of mean cleaning time, it is not possible to decide which parameters are most effective to improve cleaning. The following fluid mechanical efficiency number according to the cleaning efficiency for spray cleaning (Mauermann 2012) allows a better comparison;

$$E_{R,FF} = \frac{\text{main cleaning rate}}{\text{volumetric wetting rate}} = \frac{\bar{R}_{95}}{\Gamma_V} = \frac{0,95 \cdot m_0}{t_{95} \cdot \Gamma_V} = \frac{0,95 \cdot m_0}{\frac{V_{tot}}{B}} \quad (18)$$

This number indicates the expense in relation to benefits. Fig. 17 shows the comparison of different parameter settings. Although the cleaning time is decreasing with increasing wetting rate, the fluid mechanical cleaning efficiency decreases. The mean cleaning rate $\bar{R}_{95}$ does not increase in equal amount to the mean cleaning time $\bar{t}_{95}$ decrease, therefore the cleaning efficiency is lower. One explanation may be that simply a lower film thickness is necessary to enable the diffusion process. The exterior fluid does not contribute to the diffusion process. By using a low flow rate, the cleaning efficiency can be raised by ~60 % between $Re = 743$ and $Re = 290$. But it should be mentioned, that a complete wetting of the contaminated surface is necessary, although for $Re = 290$ in particular, it was not always possible to secure this basic requirement. However for cleaning tests this condition was guaranteed through pre-wetting of the inlet area. In production condition this requirement can be assured for instance by applying an initial high wetting rate for a short time. Obviously the most effective parameter selection has to produce a low wetting rate so resources (e.g. cleaning fluid and energy) can be saved, which brings ecological and economical benefits. If time is the most important factor to reduce down time of the facility, a high wetting rate is the best option.

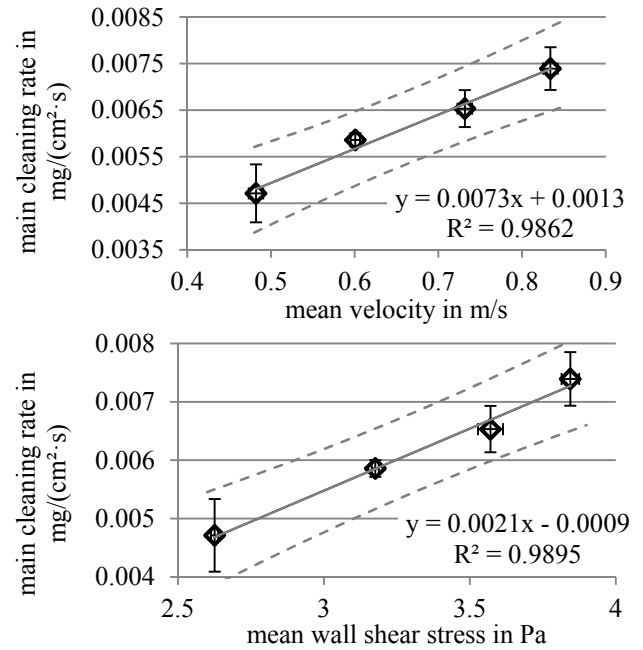


Fig. 18 Comparison of main cleaning rate and mean velocity (upper diagram), cleaning rate and mean wall shear stress (lower diagram) for a tilt angle of 30 ° (including 95 % confidence band, bars represent standard deviation)

Through comparing the flow parameters and cleaning results, correlations can be confirmed between mean velocity and main cleaning rate, as well as mean wall shear stress and the main cleaning rate for the falling film cleaning (see Fig. 18). This suggests an influence of the wall shear stress and also of the mean velocity on the cleaning behaviour for the Xanthan model soil. There is also an influence of the volumetric wetting rate, because the walls shear stress is impacted by the flow velocity gradient at the wall and hence through the wetting rate. The maximum film thickness (maximum wave height) is not a dominating factor, since it is nearly constant in the investigated Reynolds number range (see Fig. 12). The variation of film thickness through waves is also not a dominant factor, because the ratio of maximum and mean film thickness, respective to wall shear stress, is for $Re < 400$ greater than for $Re > 400$. Thus in contrast to Patel and Jordan (1970), no influence of large waves could be determined. Therefore it is generally not necessary to use a fully turbulent film flow ($Re > 400$ Brauer 1971, Kraume 2004) to clean a soil that swells easily and is removable by relatively low shear action. However, the condition of a complete wetting has to be ensured.

CONCLUSIONS

1. The determination of film thickness and its applications to derive characteristic values, such as wall shear stress and mean flow velocity for a tilt angle of 30 °, could be shown.
2. The application of a measuring method for determination of cleaning behaviour could be shown.
3. The fluid mechanical cleaning efficiency was introduced to evaluate cleaning efficiency. Consequently the flow with a low Reynolds number of

about $Re = 290$ shows the best fluid mechanical cleaning efficiency.

4. The use of a low flow rate ($Re = 290$) rather than a high flow rate ($Re = 734$) results in an increase of fluid mechanical cleaning efficiency of about 60 %. Under observance of this knowledge, it is possible to have the highest efficiency of cleaning fluid and thus resource-efficient cleaning.
5. It was demonstrated that the wall shear stress as well as the mean velocity appears to be the dominating influencing factors for cleaning of a Xanthan model soil.
6. Further work must be performed to determine the influence of other parameters, e.g. tilt angle, on cleaning and the comparison with flow characteristic. Furthermore, the influence of film surface waviness on the cleaning behaviour with, for example, frequency distribution should be evaluated.

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NOMENCLATURE

a	Factor, cm^4/mg^2
A	Area, m^2
b	Factor, cm^2/mg
B	Wetted width, mm
c	Factor, $\text{cm}^4/\mu\text{W}^2$
d	Factor, $\text{m}^2/\mu\text{W}$
E	Irradiance, $\mu\text{W}^2/\text{cm}^2$, W/m^2
e	Factor, dimensionless
$E_{R,FF}$	Fluid mechanical efficiency, $\text{mg}/(\text{cm}^2 \cdot \text{s})$ per $\text{m}^3/(\text{s} \cdot \text{m})$
g	Acceleration due to gravity, m/s^2
I_C	Intensity of the camera, grey value, dimensionless
$I_{C,max}$	Maximum intensity of the camera, grey value, dimensionless
$I_{i,1}$	Grey values before correction, dimensionless
$I_{i,2}$	Grey values after correction, dimensionless
I_{LUT}	Look up table, dimensionless
I_{Ref}	Reference, dimensionless
$I_{Ref,max}$	Maximum reference value, dimensionless
I	UV-intensity, dimensionless
k	Parameter, $1/\text{mm}$
m	Surface mass, $\text{mg}/(\text{cm}^2)$
$\bar{m}$	Mean surface mass, $\text{mg}/(\text{cm}^2)$
$\bar{m}_{min}$	Minimum mean surface mass, $\text{mg}/(\text{cm}^2)$
$\bar{m}_{max}$	Maximum mean surface mass, $\text{mg}/(\text{cm}^2)$
m_0	Initial surface mass, mg/cm^2
r	Remaining soil, dimensionless
$\bar{R}$	Radius, mm
$\bar{R}_{95}$	Main cleaning rate, $\text{mg}/(\text{cm}^2 \cdot \text{s})$
r_c	Slope of the cleaning characteristic, dimensionless
Re	Reynolds number, dimensionless

R^2	Coefficient of determination, dimensionless
Time, s	
t_{95}	Cleaning time to remove 95 % of soil, s
t_c	Typical cleaning time constant, dimensionless
V	Volume, mm^3
V_{tot}	Total Volume, m^3
$\dot{V}$	Volume flow rate, m^3/h
$\bar{w}$	Mean flow velocity, m/s
x	Direction x, mm
y	Direction y, mm
α_{pl}	Tilt angle, $^\circ$
δ	Thickness, mm
δ^+	Dimensionless film thickness, dimensionless
δ_d	Droplet height, mm
$\delta_{d,corr}$	Corrected droplet height, mm
δ_{sh}	Droplet height measured by shadow method, mm
ρ	Density, kg/m^3
τ_w	Wall shear stress, Pa
Γ_v	Volumetric wetting rate, $\text{m}^3/(\text{h} \cdot \text{m})$
ν	Kinematic viscosity, m^2/s

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