

ON THE CONCEPT OF CFD-BASED PREDICTION OF CLEANING FOR FILM-LIKE SOILS

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ABSTRACT

The removal of film-like deposits is a challenge in many fields of production. For environmental and economic reasons, the cleaning processes need to be optimised. An optimisation by means of computational fluid dynamics seems to be beneficial, but is subject to some restrictions, especially in industrial context. General modelling ideas, a subdivision into sub-processes and the significance of time dependent soil behaviour are discussed as well as specific concepts related to four basic cleaning mechanisms, namely diffusive dissolution, cohesive separation, viscous shifting and adhesive detachment. Cleaning experiments in fully developed plane channel flow, resembling a simplified plate heat exchanger, are performed with model soils (starch, petroleum jelly, ketchup) which were chosen to represent an almost ideal form of one of the basic cleaning mechanisms.

INTRODUCTION

Cleaning is an important step to ensure quality and safety during production processes. Most of the process equipment is cleaned at least daily, thus consuming a significant part of the total machine working time. Consequently, cleaning processes have a high economic and ecological impact. Many food products are processed in heat exchangers. The resulting deposits are usually film-like soils with a wide range of properties.

Through mutual interaction, this soil, the cleaning fluid and the substrate determine the cleaning behaviour. We term the combination of these three parts *cleaning system*. Statements concerning the cleaning behaviour are only valid in the context of a specific combination of all three parts. They each have properties influencing the cleaning behaviour. Material and surface properties, like roughness, surface energy or coatings and structures characterize the substrate. The cleaning fluid is usually water or an aqueous solution with a certain temperature and concentration of a cleaning agent.

Numerous studies dealing with different cleaning systems have been carried out in the past years. A wide range from pure to complex soils were

removed by different cleaning fluids at different temperatures and with various cleaning methods mostly to examine, describe or quantify specific aspects of cleaning [1].

By analysing this database, it was possible to identify different cleaning behaviours and, hence, to categorize cleaning processes. With respect to the underlying physical processes, four prototypical cleaning mechanisms, as depicted in Fig. 1, were motivated and described by several authors [2-4].

These mechanisms are ideal conceptions, whereas in reality they can change or occur simultaneously during an industrial cleaning process [5]. However, this basic classification enables the modelling of complex cleaning processes and, thus, allows for the prediction of cleaning [4,6-7].

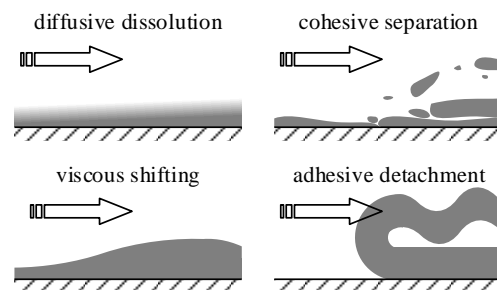


Fig. 1. Overview of cleaning mechanisms [4].

Due to the fundamental differences of the dominating physical process, the mechanisms require tailored modelling, in particular if the cleaning prediction is to be suitable for industrial application.

In this paper, after giving an overview of important processes connected to cleaning as well as model requirements regarding industrial application, specific modelling aspects and concepts are discussed. Finally, the concepts and their assumptions are evaluated based on experimental investigations in fully developed plane channel flow with model soils, each exhibiting one dominant cleaning mechanism. The aim is to describe isolated effects first and then synthesize models capable for more complex situations.

GENERAL MODELLING ASPECTS

It is a common observation, especially in the food industry, that a soil, after it comes in contact with cleaning fluid, changes one or more of its physical properties over time. As a result, the outer shape and the soil layer thickness h may change. Either the thickness increases due to swelling processes, driven by diffusion of cleaning fluid into the soil layer or it decreases due to dissolution of soil into the fluid. This is associated with a change in the local soil mass concentration β and, thus, in the local adhesion and cohesion. Similar effects can be achieved by applying a heat flow, e.g. for soils that do not react with the fluid. Melting can also occur. Generally, the change in cohesion is expressed by a change in rheological properties which needs to be included in the model by variable model parameters.

The flow velocity u of the cleaning fluid is relevant for two sub-processes. On the one hand there is the exertion of hydraulic forces on the soil by the flow. The generated shear stress τ and pressure on the surface of the soil strongly depend on the flow rate and on the geometry of the soil layer. This is why the exposed soil front side often plays a dominant role in cleaning processes. On the other hand, the flow is needed to transport separated or dissolved parts of the soil. A faster transport leads to a higher concentration gradient and can therefore enhance the cleaning progress. The quality of the prediction of the flow field is crucial in any cleaning prediction.

Regarding the temporal progression of cleaning processes, three phases may occur. Figure 2 shows them schematically in terms of the removal rate. First, the soil has to be transformed into a transportable state, i.e. detach from the soil bulk. Once the soil layer is wetted with cleaning fluid, processes like the diffusion of cleaning fluid or heat transfer into the soil layer may be initiated. Depending on the microstructure of the soil these processes may be delayed by an incubation time, e.g. due to enzymatic reactions or reptation processes. During this phase, I, the removal rate is zero. In the consecutive phase II, soil molecules or particles are transported into the cleaning fluid and further away from the soil layer. This process leads to an increasing removal rate until an equilibrium state may be reached.

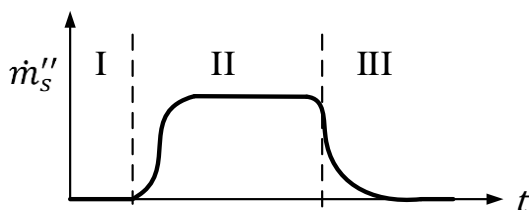


Fig. 2. Temporal progression of cleaning processes in terms of the removal rate.

Once enough soil is removed from the substrate so that only small patches remain, the cleaning process is decelerated and the removal rate decays in phase III. It is obvious that, due to the time dependency of the soil behaviour and the cleaning rate, the simulation of the mass transfer has to be transient.

This brief description already reveals the complexity of cleaning processes. The interaction of soil, cleaning fluid and substrate as well as temporally and locally variable parameters of the soil place high demands on a simulation model.

In general, the modelling of soil removal for all cleaning mechanisms mentioned above may be approached through fully temporal and spatial resolved multiphase flow simulations. This type of simulation is topic of current fundamental research and due to their high computational complexity impractical for the prediction of cleaning during the design process in industry.

In contrast to fundamental research, CFD simulation for industrial application has to keep in mind an acceptable computational effort. This can be achieved primarily at the cost of correctness. The proposed concept is based on the numerical solution of

- the Reynolds averaged Navier-Stokes equations (RANS), closed by a two-equation turbulence model for momentum transfer of the mixture of cleaning fluid and soil, using physical properties of the mixture in case of turbulent flow condition, and
- a convection-diffusion transport equation for the soil in the cleaning fluid, based on mass concentration or volume fraction and
- considering the interaction of cleaning fluid and soil layer by the use of an adequate formulation of a boundary condition at the soil layer.

This kind of modelling is limited to a specific range of properties of the cleaning system. First, the relation between the height of the soil layer and the characteristic length of the flow domain normal to the soil has to be small. Second, the surface of the soil layer has to stay smooth. Hence, only small deformations of the soil layer are permitted - particularly at the front and the back side. The acceptable range of the described limits has to be evaluated for each specific cleaning system.

In an ideal case it is possible to decouple the simulation of the flow field from the simulation of the removal process and thus additionally lower the computing time. This approach has been demonstrated by Joppa et al. [4, 8] for diffusive dissolution and cohesive separation of small particles, as described in the following chapter. Similar approaches may be developed and used in the future to model the removal of soils exhibiting the other cleaning mechanisms.

MECHANISM-SPECIFIC MODELLING

Diffusive Dissolution

Diffusive dissolution is characterized by a continuous removal of the soil from top to bottom. The process is driven by the diffusive transport of soil molecules through the boundary layer into the main flow, where at sufficiently high flow velocity, convective transport dominates. This cleaning mechanism occurs for specific combinations of cleaning fluid and soil, where the soil is soluble in the cleaning fluid. Using Fick's law of diffusion, the removal rate of soil at the interface between soil and cleaning fluid $\dot{m}_{s,h}''$ is expressed by

$$\dot{m}_{s,h}'' = -D \left. \frac{\partial \beta}{\partial y} \right|_{y=h} \quad (1)$$

where D denotes the diffusion coefficient for the binary system of soil and cleaning fluid, β the mass concentration of dissolved soil in the cleaning fluid and $\partial \beta / \partial y$ the derivative in soil normal direction at the cleaning fluid soil interface.

The highest gradient arises at the front side of the soil layer. It gradually decreases in streamwise direction as the cleaning fluid flows past the soil layer and takes up soil molecules from the soil layer. This leads to an accelerated cleaning process of the upstream soil front and a slower cleaning process with increasing distance to the upstream side of the soil layer.

The transport of detached particles can be modelled by using Eq. (2).

$$\frac{\partial \beta}{\partial t} + \nabla \cdot (\vec{u} \beta) = \nabla \cdot (D \nabla \beta) \quad (2)$$

The removal of the last remaining molecular monolayer requires additional consideration, because, independent of the otherwise dominant cleaning mechanism, it is always adhesively attached to the surface. The desired level of cleanliness determines whether this layer needs to be removed and thus considered as well.

Cohesive Separation

This mechanism is characterized by overcoming the cohesive tension σ_{co} within the soil and successive erosion of the soil layer. From a macroscopic point of view, for very small particles, the particle transport close to the surface of the soil layer is similar to diffusive dissolution. For the analogy to be valid, the lower limit of particle size is the molecular size and the upper limit is determined by the velocity boundary layer thickness. If the particle size is smaller than the viscous sublayer of the velocity boundary layer, hydrodynamic forces on the particle are small and transport is dominated by diffusion [9]. This is expressed by the dimensionless particle diameter d_p^* in Eq. (3), where

d is the particle diameter, ρ and ν are the cleaning fluid density and kinematic viscosity, respectively.

$$d_p^* = d \frac{\sqrt{\tau/\rho}}{\nu} \quad (3)$$

The results of Schöler et al. [9] and Gottschalk et al. [10] for starch and egg yolk underpin the assumption that for $d_p^* < 1$ cleaning is dominated by diffusion processes. Then, in analogy to Eq. (1), the removal rate can be calculated by

$$\dot{m}_{s,h}'' = -D_p \left. \frac{d\beta}{dy} \right|_{y=h} \quad (4)$$

replacing D by a modified diffusion coefficient D_p . The same replacement is needed in Eq. (2).

Previous publications investigate different model soils which exhibit the cohesive separation cleaning mechanism. Xin et al. [11] developed a model to describe the cleaning of whey protein concentrate. Joppa et al. [4] adapted Xin's model to perform CFD simulations for a pregelatinised waxy maize starch in plane channel flow [8].

For large particles, identified by $d_p^* > 1$, more experimental investigations and numerical modelling are required. Further aspects to this are described more in detail by Gradoń [12] as resuspension of particles from multilayer deposits, e.g. in the context of waver cleaning.

Viscous Shifting

In this case, the soil is either fluid from the beginning or becomes flowable by preceding processes like soaking, heat transfer or chemical reaction. An exemplary case is the cleaning process of two immiscible fluids like the removal of petroleum jelly by water. The hydraulic forces of the cleaning fluid on the one hand and the rheological properties of the soil on the other hand determine the flow of the soil layer.

The flow of the cleaning fluid can be simulated as a single phase flow. Following the concept to consider the interaction of cleaning fluid and soil layer as a boundary condition, there is a non-zero velocity for the cleaning fluid at the interface between soil and cleaning fluid. The formulation of the boundary condition to calculate the soil removal rate and the velocity at the interface can be expressed using lubrication film theory. The situation is drafted in Fig. 3.

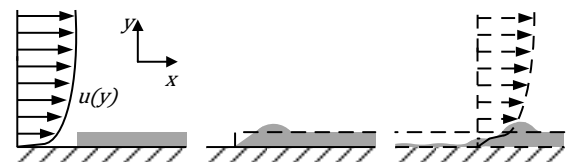


Fig. 3. Different stages of cleaning for a model soil exhibiting viscous shifting.

Specific aspects of the soil, like yield stress and non-Newtonian flow behaviour, and of the soil substrate boundary, like wall slip leading to plug flow, must be considered. One of the limitations of this approach is that viscous fingering [13, 14] should not appear or plays a negligible rule.

Yeckel and Middleman [6] were able to predict the thinning of a smooth silicone oil film by a water jet following a similar concept, i.e. coupling the shear stress and pressure distribution at the boundary of the two fluids.

In the investigations by Wilson et al. (e.g. [7]) on the cleaning of petroleum jelly by an impinging water jet, the soil layer is very thick in relation to the fluid film. The removal is dominated by pressure forces and modelled for this specific case as a fully adhesive detachment from the substrate.

Adhesive Detachment

Adhesive detachment manifests itself through the detachment of large patches of soil at a time, when the adhesion of the respective patch to the substrate σ_{ad} is overcome, accordingly to Eq. (5).

$$m_s''(x, t) = \begin{cases} 0, & \sigma > \sigma_{ad}(x, t) \\ m_{s,0}''(x), & \sigma \leq \sigma_{ad}(x, t) \end{cases} \quad (5)$$

As depicted in Fig. 4 the adhesive detachment is dominated by two superimposed processes for the majority of food soils. First, the diffusion of cleaning fluid into the soil leads to swelling and changing properties within the layer. Once the front of cleaning fluid reaches the soil-substrate interface the adhesion of the soil to the substrate changes.

Second, a mechanical stress σ is introduced by the hydrodynamic forces as a result of the flow of cleaning fluid. Once it surpasses the adhesion of a patch of soil, the soil detaches from the substrate. If the cohesive forces within the soil layer are high, the patch folds over and removes further adjacent patches, so that one large patch is removed. If the cohesive forces are low, the soil layer ruptures and a small patch is detached instead. Once a patch has been removed, it is transported within the flow. If this transport is fast compared to the time scale of the former processes it must not be considered in the numerical model.

Zhao et al. [15] stated that surface free energy of a substrate is one of the most important properties to determine the adhesion of a given soil.

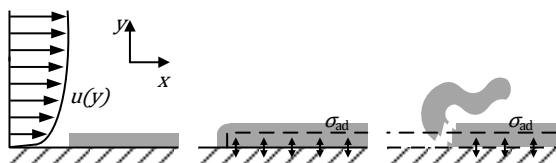


Fig. 4. Different stages of cleaning for a model soil exhibiting adhesive detachment.

For a specific cleaning system a minimum adhesion energy can be determined from the Lifshitz-van der Waals surface free energy of its components as demonstrated by Liu et al. [16].

Wilson et. al. [7] previously derived an analytical relation for the cleaned radius by an impinging water jet on a substrate soiled with adhesive soil. Upon impact on the substrate the water flows radially outwards from the impact point. The height of the resulting liquid film is of the same magnitude as the height of the soil layer. Consequently, a momentum balance at a radius is used and variations of thickness of the soil layer and adhesive strength to the substrate due to swelling are not considered.

For the cleaning of closed geometries, the height of the soil layer and the characteristic length of the component to be cleaned generally differ by at least one magnitude. The flow is redirected over the soil layer, so that the momentum balance needs to be adapted. A low viscosity at the fluid-soil interface leads to viscous shifting and plastic deformation of soil and thus a reduced load on the soil-substrate interface, which delays adhesive detachment. For a simplified model of adhesive detachment viscous shifting might be neglected if this occurs for short times only at the beginning of the cleaning process.

The mechanical load on the soil can be determined from the numerical solution of the Navier-Stokes or RANS equations. If the height of the soil layer is sufficiently small its influence on the overall flow may be neglected and a decoupled approach as has been developed for diffusive dissolution may be used.

CLEANING EXPERIMENTS

Test Soils and Application Methods

The criterion to choose the test soils was that one of the cleaning mechanism dominates the cleaning behaviour. As a result of several tests the following soils have been selected: petroleum jelly (viscous shifting), ketchup (adhesive detachment) and starch (diffusive dissolution or cohesive separation). The pre-cleaned stainless steel test sheets made of AISI 304 with a cold-rolled 2B finish ($R_z < 1 \mu\text{m}$) and dimensions of $(150 \times 80 \times 2) \text{mm}^3$ were soiled on a $90 \times 75 \text{mm}^2$ large centred subarea and subsequently dried in a climate chamber (temperature of $\vartheta = 23 \text{ }^\circ\text{C}$, relative humidity of $\phi = 50 \%$) for about 20 hours. The resulting surface soil mass coverage m_s'' was determined by differential weighing.

Petroleum jelly (CAS number: 8009-03-8, Carl Roth GmbH + Co. KG, Germany) and ketchup (RICH delicious, Tomaten Ketchup fruchtig, Netto Marken-Discount AG & Co. KG) were applied at room temperature on the test sheets. A defined thickness of the soil layer was adjusted with the aid

of spacers and a scraper blade. Starch (pregelatinised waxy maize starch, C Gel – Instant 12410, Cargill Deutschland GmbH) was mixed with fluorescent zinc sulphide tracer crystals in deionized water ($\vartheta = 30\text{ }^{\circ}\text{C}$) under stirring. The concentrations were $c = 150\text{ g/l}$ and $c = 4\text{ g/l}$ respectively. The solution was then homogeneously sprayed on the test sheets. Due to the fact that the resulting layer thickness is an order of magnitude larger than the tracer crystals the dry soil layer was smooth ($R_z < 1.6\text{ }\mu\text{m}$) [4].

Test Rig and Measuring Method

Cleaning experiments were carried out in a closed circuit test rig with controlled flow rate. It is schematically shown and described in more detail by Joppa et al. [4]. The soiled test sheets form one wall of the plane channel with a rectangular cross-section of $5 \times 78\text{ mm}^2$. The opposite wall is made of UV-transparent polymethylmethacrylate. This allows monitoring of the cleaning progress with a monochrome grayscale camera with resolutions of 14 bits and 0.17 mm per pixel. The channel window dimensions are $120 \times 78\text{ mm}^2$ and the captured pictures were cropped to a centred region of interest (ROI) with a size of $100 \times 60\text{ mm}^2$ to reduce side effects. Two ultraviolet (UV-A) lamps illuminate the soil layer on the test sheets. The used petroleum jelly and ketchup have an inherent fluorescence, while within the starch layer the added tracer fluoresces. The raw grey scale value I_{raw} is used to quantify the amount of soil in situ with spatial resolution. Opaque walls shield the test section from the environment. Purified water acts as cleaning fluid and flows through the supply channel, test section and drainage, which are aligned horizontally and provide fully developed turbulent flow. The test sheets are vertically oriented along this axis to minimize the influence of bubbles during start-up. Table 1 summarizes the conducted exemplary cleaning experiments with the corresponding parameters, namely type of soil, initial surface soil mass coverage $m''_{s,0}$, mean bulk velocity u_b , fluid temperature ϑ and resulting Reynolds number, Re .

Data Evaluation

In order to evaluate the remaining soil quantity on the test sheets over time, various influences on the raw grey value were investigated. Figure 5 shows I_{raw} as function of $m''_{s,0}$ for the three soils.

Table 1. Parameters of the cleaning experiments with exemplary test soils.

soil	$m''_{s,0}$, g/m^2	u_b , m/s	ϑ , $^{\circ}\text{C}$	Re
starch	51	2.0	22.7	19,500
petroleum jelly	367	5.0	30.8	58,500
ketchup	264	1.0	22.3	9,700

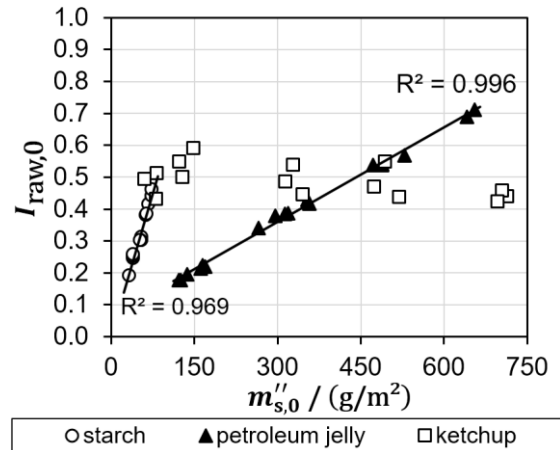


Fig. 5. Initial raw grey scale value for the three test soils under variation of the initial surface soil mass coverage $m''_{s,0}$.

For petroleum jelly the test section was filled with water while the ketchup and starch layers were dry. There is a clear linear correlation for petroleum jelly and starch, while I_{raw} is almost constant for ketchup.

Figure 6 shows the temporal progression of I_{raw} after the test section was flooded initially and u_b remained at 0 m/s for three exemplary test sheets of the soils. Petroleum jelly is unaffected by water. In contrast, the other two soils absorb water. The decreasing grey value of ketchup cannot clearly be attributed to a reduction of the soil amount. Observations showed that in addition to the absorbing process an unknown fluorescent substance diffused out of the ketchup layer and accumulated at the bottom of channel outside the ROI due to gravity. The residual ketchup structure visually remains coherent. As described earlier by Joppa et al. [8] the grey value of the tested starch layers increases during soaking due to the growing distance between the tracer crystals.

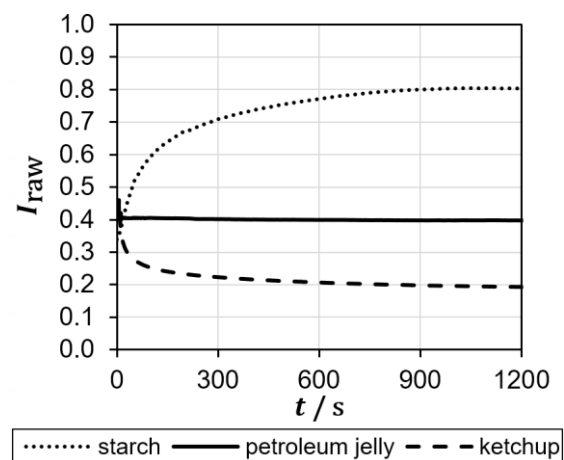


Fig. 6. Change of the raw grey scale value with time for starch ($m''_{s,0} = 67\text{ g/m}^2$), petroleum jelly ($m''_{s,0} = 338\text{ g/m}^2$) and ketchup ($m''_{s,0} = 714\text{ g/m}^2$) for pure swelling ($u_b = 0\text{ m/s}$).

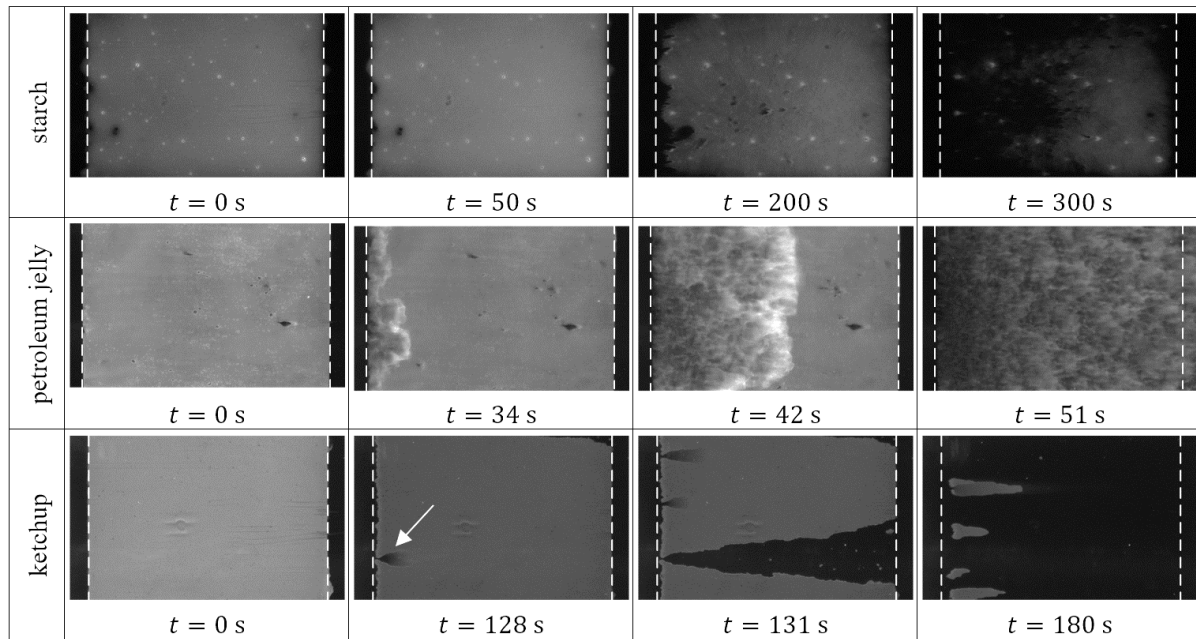


Fig. 7. Temporal progression of the three test soils while cleaning; dashed lines indicate the boundaries of the initially soiled area; total area shown is 100 mm × 60 mm; cleaning parameters in accordance to Table 1.

The authors describe a procedure for correcting this effect in order to obtain more valid data on the amount of soil. This is also used here to determine the remaining soil mass and thus the cleaning time t_{90} after which 90% of the initial amount of soil has been removed.

Photographs of completely clean test sheets inside the flooded test section were also taken and the empirical cumulative distribution function of the raw grey scale value was determined pixelwise. For a chosen threshold of $I_{raw} = 0.08$, less than 1% of all pixel were higher than this value. Likewise, 99 % of all pixel of a ketchup layer were above this value, even after soaking for 1500 s. This enabled a binary distinction between clean and still soiled subareas. In terms of petroleum jelly this implies a residual soil amount of less than 20 g/m².

For evaluating the cleaning tests, the ROI was subdivided in 1 × 1 mm² large subareas, wherein an average was taken over about 36 pixels. Subsequently either t_{90} or a binary information was determined locally for starch or ketchup/petroleum jelly respectively. Averaging the two dimensional data in a vertical direction provides information about the cleaning progress in flow direction. For ketchup and petroleum jelly t_{90} was determined at the time when 90% of the 60 vertical subareas were detected as clean.

RESULTS AND DISCUSSION

Figure 7 depicts the cleaning progress of starch, petroleum jelly and ketchup, whereby dashed lines limit the initially soiled area.

The starch layer at $t = 50$ s is brighter than at the beginning, however no cleaning is visible. The brightest spots are agglomerates of the tracer crystals, which could not be fully suspended. At $t = 200$ s completely clean areas become visible at the front edge and partly in the first half of the soil layer. This effect is intensified at $t = 300$ s, where cleaning also takes place at the rear edge. In general, the entire soil layer gets darker, indicating a process of soil removal from top to bottom.

The deformation of the petroleum jelly layer starts almost from the beginning but only at the front edge. Changes in grey value indicate areas with a thinner and a thicker layer than the initial soil layer. A clear effect of viscous fingering is not present. Instead, an almost linear wave of soil moves over the uninfluenced layer behind. This also leads to the effect that the initially clean area at the end becomes temporarily soiled. During the remaining cleaning process, the entire soil layer gets thinner. Progressively smaller waves are visible on the soil layer which move regularly in the direction of the flow.

The adhesive detachment of ketchup begins at a small point on the front edge and expands rapidly in the shape of a funnel. This process is repeated at several points on the front edge. It can be observed that the front edge moves slightly in the direction of the flow. Up to now it cannot be clearly determined whether there is a deformation, in terms of viscous shifting, or an adhesive removal of small chunks. In some cases, remaining patches like at $t = 180$ s move slowly but coherently over the substrate up the point where they accelerate and are transported away by convection of the flow.

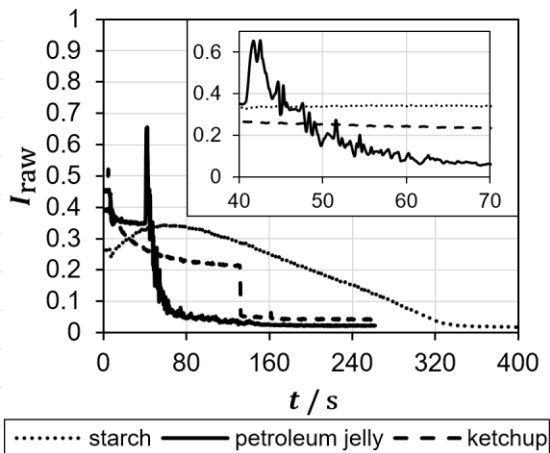


Fig. 8. Change of the raw grey scale value with time for a centred 1 mm^2 large subarea in relation to Fig. 7 for the three model soils; cleaning parameters in accordance to Table 1; inset emphasizes the wavy character of the removal of petroleum jelly.

Figure 8 shows the temporal progression of the raw grey scale value for the centred 1 mm^2 large subarea of the same experiments as in Fig. 7. The discussed soil specific effects become apparent here. Changes in grey value during the first 10 s are related to reflections at the air-water phase boundary until the test section is completely flooded. For starch, the grey value increases first and then decreases almost linearly until the final decay phase. For petroleum jelly, after an almost constant phase, the grey value shows a peak due to the wave passing through, followed by a rapid, but slightly wavy decrease. The grey value of the ketchup soil layer continuously decreases as in the experiment of Fig. 6. The sudden adhesive removal is expressed by one steep drop below the threshold for an unsoiled test sheet.

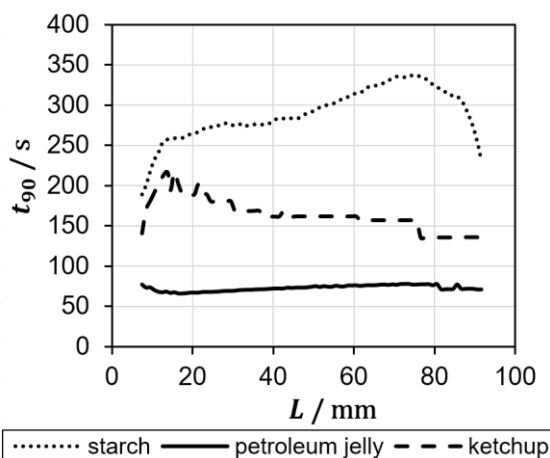


Fig. 9. Experimental results of the local cleaning time t_{90} for the three model soils; cleaning parameters in accordance to Table 1.

The local cleaning time t_{90} is shown in Fig. 9. For starch, it reaches its lowest values at the upstream and downstream end of the soil layer. The downstream end takes about 50 s longer. The cleaning time increases with increasing distance to the front edge and reaches a maximum at $L = 78 \text{ mm}$ which is approximately 60 % higher than at the edges. For petroleum jelly the cleaning time is almost constant and only alters by $\pm 8 \%$ around its mean value. Similar to starch, t_{90} is lowest at the upstream and downstream edge for ketchup, while the maximum is at $L = 15 \text{ mm}$ and 55 % higher than at the edges. This is related to the funnel shaped removal beginning at the front edge.

CONCLUSION

Cleaning is a complex process that can be tackled by classification regarding prototypical cleaning mechanisms, subdivision into sub-processes and assumption of a general temporal procedure. Cleaning experiments with mechanism-specific model soils support the development of prediction models.

Regarding a starch layer, the transport of cohesively separated small particles is limited and modelled by a diffusive process. The viscous petroleum jelly layer is being displaced by the flow and shifted out of the considered area while ketchup detaches adhesively from the substrate. Cleaning tests with these exemplary model soils underpin the need for visual inspection and qualitative description of the removal process as a first step. The fluorescent properties of the soil layers, either inherent or by adding a tracer, allow a quantitative evaluation of the cleaning progress. Care must be taken when interpreting changes in grey values, as they are not to be interpreted exclusively as cleaning. The front and end edge of soil layers should be taken into account more, as the cleaning time there may differ significantly from the rest of the soil layer.

Further cleaning tests with these test soils will be carried out with dedicated focus on this. Attempts will be made to measure the height and shape of the soil edges before and while cleaning to improve the predictive capability of the models.

ACKNOWLEDGMENTS

This research project is supported by the Industrievereinigung für Lebensmitteltechnologie und Verpackung e. V. (IVLV), the Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e. V. (AiF) and the Federal Ministry of Economic Affairs and Energy (IGF 19968 BR).

NOMENCLATURE

A	area, m^2
c	concentration, kg/m^3
D	diffusion coefficient, m^2/s
D_{hyd}	hydraulic diameter, $D_{hyd} = 4A/P$, m
D_p	modified diffusion coefficient, m^2/s
d	particle diameter, m
d_p^*	dimensionless particle diameter, –
h	soil layer thickness, m
I	intensity, –
L	length, m
m_s''	surface soil mass coverage, kg/m^2
\dot{m}_s''	soil removal rate, $kg/(m^2s)$
P	wetted perimeter, m
R_z	roughness, μm
Re	Reynolds number, $Re = u_b D_{hyd}/\nu$, –
t	time, s
t_{90}	time when 10 % of the soil remain, s
u	velocity, m/s
x	wall parallel coordinate, m
y	wall normal coordinate, m
β	mass concentration, kg/m^3
ϑ	temperature, $^{\circ}C$
ν	kinematic viscosity, m^2/s
σ	tension, Pa
τ	shear stress, Pa
ρ	density, kg/m^3
ϕ	relative humidity, –

Subscript

0	initial
ad	adhesion
b	bulk
co	cohesion
hyd	hydraulic
p	particle
raw	original
s	soil

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