# PREDICTION OF CLEANING BY MEANS OF COMPUTATIONAL FLUID DYNAMICS: IMPLICATION OF THE PRE-WETTING OF A SWELLABLE SOIL

M. Joppa<sup>1</sup>, H. Köhler<sup>2</sup>, F. Rüdiger<sup>1</sup>, J.-P. Majschak<sup>2</sup> and J. Fröhlich<sup>1</sup>

<sup>1</sup> Institute of Fluid Mechanics, Technische Universität Dresden, 01062 Dresden, Germany, matthias.joppa@tu-dresden.de <sup>2</sup> Institute of Natural Materials Technology, Technische Universität Dresden, 01062 Dresden, Germany

#### ABSTRACT

The cleaning behaviour of a pre-wetted soil is studied experimentally and modelled numerically for the prototypical case of plane channel flow. One of the channel walls is soiled with a food-based model soil containing luminescent tracer particles to perform space- and timeresolved investigations of the cleaning process. Pre-wetting is applied for a few minutes before the soil removal is started with flow of Reynolds number up to 20000. Physical model and simulation are based on a transient boundary condition to represent the behaviour of the soil. Pre-wetting is taken into account by an initial removal of a certain amount of soil due to cohesive separation and the subsequent cleaning modelled as being limited by a diffusive process. Compared to a conventional multiphase simulation, the computation time is lowered by about three orders of magnitude. The results obtained with this elementary approach match the experiments astonishingly well.

# **INTRODUCTION**

Following Fryer and Asteriadou (2009) and Goode et al. (2013), the reliable prediction of cleaning processes is of substantial interest for different kinds of industries. When processing food, pharmaceutical products or crude oil, for example, fouling or soiling of the equipment is unavoidable. If not duly removed this can result in significant hazards to consumers or a dramatic decrease in production efficiency and cause high economic losses. Moreover, cleaning induces additional costs, so that optimizing the effort while warranting safety is important.

Process simulation could be applied to optimise cleaning processes by finding optimal parameters or predicting the process time. It is generally faster and cost-effective without requiring too many experimental tests. Complex fluid dynamic simulations are the state of art, but these require a physical model as a starting point. Cleaning processes, however, are hard to model and not as widely addressed as other topics, so that reliable, versatile models are not available up to now. Developing such models and the related numerical solution process is the long-term goal of the present authors. Cleaning models in the literature show various approaches. For example, in Jensen et al. (2005) and Bach et al. (2006) the cleaning time is related to a single physical quantity of the flow field, e.g. the wall shear stress. In this case, the interaction between the flow and the soil is not modelled explicitly. Another type of process models includes this interaction but is limited to specific kinds of flow, e.g. impinging jets as an abstraction for rotary jet heads like in Yeckel and Middleman (1987), Wilson et al. (2015) and Bhagat et al. (2017). Latest approaches, e.g. Pérez-Mohedano et al. (2017), try to transfer cleaning results from lab-scale experiments and target the application to industrial problems like the cleaning of dishwashers.

The key of constructing a versatile cleaning model is to apply relevant physical mechanisms rather than using empirical correlations between input parameters of the cleaning device and output quantities expressing the cleaning effect. A comparative overview of the four relevant cleaning mechanisms, which are diffusive dissolution, cohesive separation, viscous shifting and adhesive detachment, was given first in Welchner (1993), later in Fryer and Asteriadou (2009) and lastly in Bhagat et al. (2017). A schematic overview is given in Fig. 1. The present authors rely on these mechanisms to divide the complex problem of a cleaning simulation into subproblems that are easier to tackle.



Fig. 1 Overview of cleaning mechanisms.

For the cleaning of heat exchangers in food industry applications, soils with physical properties that depend on the wetting time are of major importance. There, pre-wetting can be used to weaken the soil layer and enhance the efficiency of the cleaning process without noteworthy consumption of cleaning fluid. In Joppa et al. (2017) the present authors reported experiments and cleaning simulations in plane channel flow for a swellable soil, accounting for the fact that the properties of the soil change with time. The soil was removed by applying a constant mean bulk velocity from the beginning on. This approach is suitable if cohesive separation of only small soil particles is the dominant mechanism, with the latter being limited by the diffusive swelling process. With respect to the limiting swelling process, removal and transport in the bulk were modelled in analogy to diffusive dissolution with a constant diffusion coefficient.

In the present study, the soil is pre-wetted by the cleaning fluid under stagnant conditions for a certain time before starting the flow. A diffusive process causes soaking and swelling, lowering the cohesive forces and mobilising the soil. If the weakened layer is exposed to mechanical stress, special attention has to be paid to cohesive separation and viscous shifting. Accounting for the unsteady deformation of the fluid-soil interface (Fig. 1, bottom left) is delicate and computationally costly. To make the situation tractable in view of industrial applications, this process is represented by a suitably modelled initial phase of removal described below, which is followed by subsequent cleaning in the diffusion dissolution regime. The model is validated by own experiments on the removal of starch in plane channel flow, which resembles the cleaning of a plate heat exchanger in the food industry.

## **CLEANING SIMULATION**

#### Physical modelling

Fundamentally, the cleaning process is split into three phases, reflecting the sequence of dominant physical mechanisms when cleaning pre-wetted soils. First, the initially dry soil swells under stagnant conditions after getting into contact with the cleaning fluid, leaving a weakened and mobilised soil layer with non-negligible extent. In that phase, the removal rate is not significant. Second, after starting the flow, the weakened layer is exposed to mechanical stress for the first time. As a result, a large part of the layer is removed in a very short period. Following the experiments of the present authors, two cleaning mechanisms could be responsible: viscous shifting and cohesive separation. Third, the cleaning mechanism switches to cohesive separation and conveying of only small soil particles, limited by the continuous diffusive swelling process. This induces a substantial increase of the time scale.

A cleaning model dealing with the removal mechanism of the last phase was already proposed and validated by the present authors in Joppa et al. (2017). There, a novel approach was used to account for the behaviour of the soil: a transient Dirichlet boundary condition for the mean volume fraction of soil,  $\varphi$ , is applied in the simulation. This approach is based on several assumptions. First, the flow is not influenced by the thickness and shape of the soil layer. Second, the material parameters of the cleaning fluid are not changed by the dissolved soil. Third, a hydraulically smooth soil layer is assumed throughout the cleaning process. Following these assumptions, flow and mass transfer decouple and a two-step simulation procedure can be employed, strongly decreasing the calculation time.

The mean flow field, described by the Reynolds averaged Navier Stokes equations (RANS) with the SST turbulence model of Menter (1994), is solved first. Then, the computed velocity field is used to determine the mass transfer. Its unsteady convection and diffusion are described with an unsteady RANS (URANS) approach, as the boundary condition for  $\varphi$  introduces an unsteadiness. As in Joppa et al. (2017), the molecular diffusion coefficient is chosen to be  $D = 10^{-8} \text{ m}^2/\text{s}$ , which is approximately three orders of magnitude larger than the value measured in experiments. Hence, the boundary layer of the mass transport is artificially thickened, lowering the high demands on the grid. Inside the flow, turbulent diffusion is represented by an additional turbulent diffusion coefficient  $D_t = v_t/0.7$ .

The model described above is extended to cover the complicated situation encountered with pre-wetting. The basic idea of the extension is illustrated in Fig. 2: The previous model proposed by Joppa et al. (2017) is applied after exceeding  $t_{pw}$ , the end of the pre-wetting phase. The initial phase of the removal prior to  $t_{pw}$  is modelled in form of a lowered initial surface soil coverage  $m''_{s}$ 

$$m_{\rm s}''(t_{\rm pw}) = m_{\rm s,0}'' - \Delta m_{\rm s,pw}'',$$
 (1)

where  $\Delta m''_{s,pw}$  is the amount of soil that is removed when the flow is turned on. The timescale of this removal is negligible compared to the duration of the subsequent diffusive phase.



Fig. 2 Schematic development of the surface soil coverage  $m_{\rm s}^{\prime\prime}$  (top) and the mean volume fraction of soil  $\varphi$  (bottom) at the surface of the soil layer  $\varphi_{\rm w}$  illustrating the basic idea of the removal model.

The boundary condition for  $\varphi$  then reads

$$\varphi_{\rm w} = \begin{cases} 0, & t < t_{\rm r} \\ \alpha_{\rm pw} \, \alpha_{\rm d} \, \varphi_{\rm max} \, {\rm e}^{C_{\rm sw}(t-t_{\rm r})} / (\Psi + {\rm e}^{C_{\rm sw}(t-t_{\rm r})}), \, t \ge t_{\rm r} \end{cases}$$
(2)

There, a small change in comparison to the model of Joppa et al. (2017) is introduced to reduce the number of model parameters. The reptation time  $t_r$  and the parameters  $C_{sw}$ ,  $\varphi_{max} = 0.74$  and  $\psi$  have not changed. The new variable  $\alpha_d$  accounts for the decay phase at the end of the cleaning

process. This phase shows an asymptotically decreasing removal rate  $m_{s'}''$  and begins when  $m_{s,d}''$  decreases below a critical soil surface coverage:

$$\alpha_{\rm d} = \min(1, m_{\rm s}''(t)/m_{\rm s,d}''). \tag{3}$$

The variable  $\alpha_{pw}$  controls the starting point of the removal:

$$\alpha_{\rm pw} = \begin{cases} 0, & t < t_{\rm pw} \\ 1, & t \ge t_{\rm pw} \end{cases}$$
(4)

At walls covered by this boundary condition, the removal rate is calculated by Fick's law of diffusion

$$\dot{m}_{\rm s}^{\prime\prime} = -R \, ({\rm d}\varphi/{\rm d}y)_{\rm w},\tag{5}$$

where *R* denotes a removal coefficient that depends on the soil. The present surface soil coverage  $m_s''(t)$  is stored in each boundary cell. Knowing the removal rate  $\dot{m}_s''$ , it is decreased in each time step.

The amount of soil that is immediately removed when the flow is turned on,  $\Delta m_{s,pw}''$ , is modelled as cohesive separation of a soil featuring a critical shear stress  $\tau_0$ . Alternatively, neglecting the duration of the removal and the deformation of the fluid-solid interface, this approach could be interpreted as removal by viscous shifting. The idea is illustrated in Fig. 3: After pre-wetting, the soil is swollen with a given profile of the volume fraction  $\varphi(y, t_{pw})$ .



Fig. 3 Removal by cohesive separation at the time  $t_{pw}$ , the end of pre-wetting, shown for the representative case of  $t_{pw} = 240$  s, Re = 10000 and  $m''_{s,0} = 36$  g/m<sup>2</sup>: Qualitative grey scale plot of the soil after pre-wetting (left), soil distribution and yield stress as a function of the wall-normal coordinate (middle) and grey scale plot of the soil after removal (right).

The yield stress of the soil is a monotonous function of  $\varphi$  and therefore also a function of y, decreasing in wallnormal direction. Turning on the flow gives rise to a wall shear stress between cleaning fluid and soil layer. The assumption now is that the part of the layer immediately being removed corresponds to the volume where the yield stress  $\tau_0$  is lower than the wall shear stress  $\tau_w$  applied by the flow at the top of the soil. Consequently, the shift-off-height

$$y_{\rm pw} = y(\tau_0 = \tau_{\rm w}) \tag{6}$$

can be used to calculate  $\Delta m_{s,pw}^{\prime\prime}$  by

$$\Delta m_{\rm s,pw}^{\prime\prime} = m_{\rm s,0}^{\prime\prime} - \int_0^{y_{\rm pw}} \rho_{\rm s} \, \varphi(y, t_{\rm pw}) \, \mathrm{d}y \,, \qquad (7)$$

where  $\rho_s$  denotes the density of the soil.

Based on the assumptions shown in the previous section, the wall shear stress can be approximated by the wall shear stress generated by the flow in a clean channel. The dependency between the volume fraction of soil and the yield stress  $\tau_0(\varphi)$  has to be measured in experiments. The soil distribution after pre-wetting,  $\varphi(y, t_{pw})$ , is calculated based on a diffusion equation. Its swelling behaviour is modelled by a diffusion coefficient that depends on  $\varphi$  as proposed by Fujita (1961). It reads

$$D_{\rm pw} = D^* \, e^{\beta^* \, \varphi}, \tag{8}$$

where  $D^*$  and  $\beta^*$  denote model parameters.

## **Computational Setup**

Altogether, the simulation consists of four main steps:

- 1. Calculate the soil distribution in the pre-wetted soil layer
- 2. Calculate the mean flow field
- 3. Predict the amount of soil that is immediately removed when the flow is turned on,  $\Delta m_{s,pw}''$
- 4. Use the results as input for the URANS simulation of the mass transfer.

While step 3 can be solved analytically, the other steps are treated numerically. The OpenFOAM framework is used to solve their fundamental equations employing a Finite Volume method of second order. The RANS equations are solved by the PISO algorithm, enhanced by outer loops and under-relaxation. In case of the mass transfer, a first-order implicit time-stepping is used.

Figure 4 shows a sketch of the two-dimensional computational domain used in step 4, which gives an impression of the boundary conditions. The mesh consists of 18500 cells at the highest Reynolds number occurring. Increasing cell sizes in wall-normal direction and local refinement in the near-wall-area ensure a dimensionless wall distance of  $\Delta y_w^+ \approx 0.5$  in all simulations. In simulation steps 1 and 2, only the wall-normal coordinate *y* is taken into account for quasi-one-dimensional domains.



Fig. 4 Sketch of the two-dimensional domain used to simulate the removal of a pre-wetted soil in plane channel flow (not to scale). The initial length of the soil layer is  $L_s$ ,  $\delta$  denotes half of the channel height.

The mean flow field is calculated by employing a symmetry boundary condition at the top, periodic conditions in streamwise direction and a no-slip condition at the bottom wall. The mass transfer simulations feature homogeneous Neumann conditions for  $\varphi$  at the left, the right and the upper boundary. In step 1, the simulation of pre-wetting, this holds for the bottom wall as well. However, in step 4, the soil layer is not included in the domain but modelled by a transient Dirichlet condition as described in the previous section. On the clean part of the wall  $\varphi = 0$  is applied.

The calculation time of a whole cleaning simulation using one core of a standard PC with a speed of 1.2 GHz is about one hour. An alternative simulation using a conventional multiphase approach on a very coarse grid with four cell layers inside the dry soil layer, also run by the present authors but not reported here, needed two weeks on eight cores. Hence, the approach presented here lowers the calculation time by at least three orders of magnitude.

## PARAMETRISATION AND CLEANING TESTS

#### **Cleaning Experiments**

Soiling procedure. First, the model soil, a pregelatinised waxy maize starch named C Gel – Instant 12410 and produced by Cargill Deutschland GmbH, was mixed with fluorescent zinc sulphide tracer crystals in deionized water under stirring. The concentrations were c = 150 g/l and c = 4 g/l respectively. For cleaning experiments, the homogeneous suspension was then evenly sprayed on precleaned test sheets made of AISI 304 with a 2B finish  $(R_z \le 1 \,\mu\text{m})$  on an area of  $A = 150 \times 80 \text{ mm}^2$ . Finally, the sheets were dried in a climate chamber (temperature of  $\vartheta = 23$  °C, relative humidity of  $\phi = 50\%$ ) for about 20 hours. The dry soil layer is smooth  $(R_z \le 1.6 \,\mu\text{m})$  because the resulting layer thickness is an order of magnitude larger than the tracer crystals.

Test rig. A closed loop cleaning test rig as described in detail in Joppa et al. (2017) was used to study cleaning in plane channel flow. Deionized water ( $\vartheta = 25 \text{ °C} \pm 1 \text{ °C}$ ) flows through a transparent channel test section with a cross sectional area of  $A = 78 \times 5 \text{ mm}^2$  and a bottom formed by a soiled test sheet. Fully developed turbulent flow is ensured by appropriate dimensions of the supply channel and drainage. The tested mean bulk velocities of  $u_{\rm b} = 0.5$  m/s, 1 m/s and 2 m/s, with corresponding Reynolds numbers of Re = 5000, 10000 and 20000 respectively, were adjusted by a control loop consisting of flow rate sensor, computer and a servo-motor driven pump. For pre-wetting, the test section was flooded driven by the gravitation within T = 30 s. After a total pre-wetting time of  $t_{pw} = 120$  s or  $t_{pw} = 240$  s, the pump was started with an acceleration of  $a = 0.05 \text{ m/s}^2$ . The closed loop control allowed an overshooting as a compromise to obtain the target velocity quickly.

*Transient measurement of soil removal.* The transparent channel test section is surrounded by lightproof walls. Inside these walls, UVA lamps are mounted that excite

the fluorescent tracer within the soil. A camera with a monochromatic sensor and fourteen bits resolution captures the fluorescence intensity of the soil during pre-wetting and cleaning in situ. The average grey scale value, I, was obtained for each picture based on a centred region of interest of  $A = 40 \times 40$  mm<sup>2</sup>.

Figure 5 shows a typical development of the raw grey scale value for  $u_b = 1 \text{ m/s}$  and  $t_{pw} = 0 \text{ s}$  (instantaneous start of the pump). Assuming a linear relation between *I* and the amount of soil as well as a continuous removal, the grey scale value is expected to decrease monotonically. Instead, it shows a strong increase at the beginning. This discrepancy was already discussed in very detail in Joppa et al. (2017) and can be attributed to a change of optical soil characteristics due to swelling.

In the former publication, a simplified approach was used by neglecting any cleaning before the maximum grey scale value. In the meantime, additional tests were performed to better distinguish between the change of the grey scale value due to swelling or cleaning. Therefore, pure swelling processes were captured with  $u_b = 0$  m/s and  $t_{pw} = 1000$  s for different amounts of initial soil mass ranging from  $m_{s,0}'' = 26$  g/m<sup>2</sup> up to  $m_{s,0}'' = 67$  g/m<sup>2</sup>. These grey scale value curves were monotonically increasing. To deal with this issue, the correction formula

$$I_{\rm cor}(t) = I_{\rm raw}(t) / \left(\frac{p t}{q+t} + 1\right)$$
(9)

with the parameters

$$p = 1.1807 \ e^{0.0327 \ m_{s,0}/g/m^2} \tag{10}$$

and

$$q = 13.5 \text{ s } e^{0.317 \frac{m_{s,0}'}{g/m^2}}$$
 (11)

was developed and applied to the measured grey scale values. As a result, the values of each test case remained constant within bounds of five percent.



Fig. 5 Development of the grey scale value, *I*, for  $u_{\rm b} = 1 \text{ m/s}, \ m_{\rm s,0}^{\prime\prime} = 60 \text{ g/m}^2$  and  $t_{\rm pw} = 0 \text{ s}$  with respect to several correction procedures.

Assuming a similar behaviour in the cleaning tests, equation (9) was applied to their measurement data. Figure 5 shows the positive effect of this correction method by opposing its result to the raw data and the result of the previously used correction algorithm for a representative case.

## Parametrisation of the Removal Model

Swelling behaviour. To measure pure swelling of the soil resembling the behaviour in the pre-wetting phase, test sheets with size  $A = 40 \times 20 \text{ mm}^2$  were soiled by using a wiper resulting in initial surface soil coverages of  $m_{s,0}^{\prime\prime} \approx 60 \text{ g/m}^2$ . After drying, these test sheets were placed horizontally in a transparent container filled with deionized water. The growth of the soil was then captured by a camera for T = 20 min. The upper edge of a test sheet was in alignment with the vertical middle of the camera's sensor to minimize distortion. By using the image processing software ImageJ, the swollen soil layer thickness was extracted and used to manually parametrise the swelling model of simulation step 1, assuming that the thickness of the soil layer, *h*, is described by  $h = y(\varphi = 0.01)$ . The final model constants read  $D^* = 5.5 \cdot 10^{-12} \text{ m}^2/\text{s}$  and  $\beta^* = 20$ . The very good agreement of the measurement and the results of the associated simulation is illustrated in Fig. 6.



Fig. 6 Growth of a soil layer thickness due to wetting: results of experiments and simulation.

**Rheological properties of the soil.** Solutions of starch in water at different concentrations were characterized by rheological measurements to gain information of their flow behaviour. Each sample resembles a specific swelling grade of the soil layer. The concentration ranged from c = (1 g starch)/(100 g water) to c = 17 g/100 g. Every concentration was mixed twice. Each batch was measured after waiting one day twice with a MCR 300 rheometer (Anton Paar) and an appropriate measuring system in rotation at  $\vartheta = 23 \text{ °C}$ . Shear rates ranging from  $\dot{\gamma} = 0.01 \text{ s}^{-1}$  to  $\dot{\gamma} = 1000 \text{ s}^{-1}$  were applied. The results showed a shear-

thinning behaviour and were subsequently fitted to the Herschel-Bulkley model which describes the shear stress in a fluid by  $\tau = \tau_0 + K \cdot \dot{\gamma}^n$ , where  $\tau_0$  denotes the yield stress, *K* is called consistency index and *n* is the so-called flow behaviour index. The measured yield stresses were fitted to a power-law. Based on the result of other measurements, the densities of starch and water were said to be identical. Consequently, the concentration could be converted into the volume fraction by  $\varphi = c/(1 + c)$ , resulting in

$$\tau_0 = 73476 \,\mathrm{Pa} \cdot \varphi^{4.594} \,. \tag{12}$$

**Parameters of the boundary condition.** The cleaning experiments with  $t_{pw} = 0$  s of Joppa et al. (2017) were reevaluated by applying the swelling correction with Eq. (9) and using the same determination procedure. The new model parameters are listed in Table 1. Now all of them, R,  $t_r$ ,  $C_{sw}$ ,  $\Psi$  and  $m''_{s,d}$ , are soil dependent parameters that do not depend on the flow. Therefore, the cleaning model is not limited to the test case of the plane channel flow used here, but can be used in arbitrary complex flow fields. The reptation time  $t_r$ and the removal coefficient R depend on  $m''_{s,0}$ , whereas the other parameters are constant.

Table 1 Summary of parameters used to model the soil's behaviour to simulate the cleaning process of a starch based soil.

No.	$m_{\rm s,0}^{\prime\prime}$ in	$m_{\rm s,d}^{\prime\prime}$ in	t <sub>r</sub> in	R in	$C_{\rm sw}$ in	Ψ
	g/m <sup>2</sup>	$g/m^2$	S	g/(m s)	s <sup>-1</sup>	
1	30	5.8	7.0	$1.42 \cdot 10^{-5}$	0.67	4.4
2	40	5.8	12.3	$1.28 \cdot 10^{-5}$	0.67	4.4
3	50	5.8	19.1	$1.14 \cdot 10^{-5}$	0.67	4.4

## **RESULTS AND DISCUSSION**

#### **Initially removed Soil**

As described above, the calculation of the amount of soil removed by cohesive separation at the end of the pre-wetting,  $\Delta m_{s,pw}''$ , is solely based on physically motivated model constants and assumptions. No empirically determined parameters were included. Thus, the results shown in Fig. 7 are quite extraordinary. There, predicted values of  $\Delta m_{s,pw}''$  are displayed together with measured values of own experiments for several Reynolds numbers, *Re*, and initial surface soil coverages,  $m_{s,0}''$ .

In Fig. 7 (right), the pre-wetting time is  $t_{pw} = 240$  s. The overall agreement between experiment and simulation is good. This holds especially for low Reynolds numbers. In both, the experiment and the simulation,  $\Delta m''_{s,pw}$  is decreasing with growing  $m''_{s,0}$ . This behaviour was not expected and has to be further investigated in the future. Having Re = 20000, the prediction expects most of the soil to be initially removed. Hence, the decrease of  $\Delta m''_{s,pw}$  is not visible. Additionally, the comparison between experimental and simulation results reveals an overestimation at high  $m''_{s,0}$ .



Fig. 7 Experimental and simulation results on the amount of soil removed by cohesive separation,  $\Delta m''_{s,pw}$ : Pre-wetting times of  $t_{pw} = 120$  s (left) and  $t_{pw} = 240$  s (right). Open and closed symbols show results from simulations and experiments, respectively. The solid line represents the special case, when the soil layer is completely removed. The other lines are linear fit curves of the experimental data.

Figure 3 gives an impression of the reason: The profile of the volume fraction of soil,  $\varphi(y)$ , is very steep in the near wall region. A small mistake at the prediction of the yield stress profile or the wall shear stress will give large deviations of  $\Delta m_{s,pw}^{"}$ . The most likely cause of the error is that the swelling model underestimates the value of  $\varphi_w$  and overestimates the gradient of  $\varphi$  at the wall.

In Fig. 7 (left), the results for a smaller pre-wetting time of  $t_{pw} = 120$  s are shown. For Re = 20000 the agreement is good, whereas  $\Delta m_{s,pw}^{\prime\prime}$  is underestimated for the lower Reynolds numbers. Here, better simulation results were possible, if the swelling model would give higher gradients of  $\varphi$  far from the wall. The overshooting of the velocity is not the reason of this deviation because it was considered by the authors when calculating  $\Delta m''_{s,pw}$ : the maximum value of the velocity was used to calculate the wall shear stress.

# **Cleaning Time**

To verify the simulation model's capability of predicting the cleaning of a pre-wetted soil, the time  $t_{90}$ , when 90 percent of the initial mass of soil have been removed, is compared to own experimental results. Figure 8 (right) shows the values for several Reynolds numbers, Re, and initial surface soil coverages,  $m''_{s,0}$ , after a pre-wetting time of  $t_{pw} = 240$  s. The cleaning experiments are the same as in Fig. 7 (right). For the simulation, the pre-wetting time was



Fig. 8 Cleaning time  $t_{90}$  after a pre-wetting time of  $t_{pw} = 120$  s (left) and  $t_{pw} = 240$  s (right) in own experiments and based on simulations. Open and closed symbols show results from simulations and experiments, respectively. The straight lines are linear fit curves of the experimental data.



Fig. 9 Representative development of the surface soil coverage,  $m_s''$ , (left) and the removal rate,  $\dot{m}_s''$ , (right) in own experiments and based on simulations:  $m_{s,0}'' = 36 \text{ g/m}^2$ ,  $t_{pw} = 240 \text{ s}$ , Re = 10000. The snapshot is taken from the experiment.

enhanced to account for the acceleration phase of the cleaning fluid in the experiment. It was calculated using

$$t_{\rm pw}^* = t_{\rm pw} + u_{\rm b}/a$$
 (13)

The overall qualitative and quantitative agreement is very good. Having a closer look, the simulation results for Re = 20000 are arranged in a nearly horizontal line because  $m''_{s,0} = \Delta m''_{s,pw}$  virtually holds as it was discussed before. Further, the cleaning times in case of Re = 5000 are underestimated. This is caused by the model constant R, which is mainly valid for fully turbulent flows.

In case of a lower pre-wetting time, as illustrated in Fig. 8 (left), the agreement between experiment and simulation is even better. The predicted cleaning times are within the experimental uncertainty. As this could not be expected with respect to the large deviations at predicting  $\Delta m_{s,pw}''$ , there must be an erroneously neglected physical effect compensating for the underestimation of  $\Delta m_{s,pw}''$ . This effect is also present at the higher pre-wetting time. Fig. 8 (right) reveals for Re = 10000 that the cleaning time tends to be overestimated although  $\Delta m_{s,pw}''$  was calculated correctly.

In Fig. 9 (left), the surface soil coverage  $m''_s$  is shown as a function of time. It is clearly visible that, generally, the model idea fits the physical behaviour well. Nevertheless, some deviations have to be explained. First, in the experiment, the amount of soil,  $m''_s$ , is decreasing in the prewetting phase. This could the result of an over-correction by Eq. (9). It could also be due to the removal of soil when the channel is flooded since there is a mean bulk velocity of  $u_b \approx 1 \text{ m/s}$  for a period of  $T \approx 30 \text{ s}$ . However, Fig. 5 proves that the amount of soil removed by that flow pulse is small. Consequently, the swelling correction has to be revised.

A second difference is a deviant size of the constant removal rate after the initial cohesive separation has taken place. The removal rate  $\dot{m}_{s}^{\prime\prime}$  is plotted as a function of time in Fig. 9 (right). This figure additionally contains a snapshot from the experiment showing a wave-structured surface of the soil. It is obvious that the simulation model does not include this effect because it assumes a smooth surface of the soil. The shape, cause and impact of the surface structure have to be further investigated in order to include this effect in the model in the future.

### CONCLUSIONS

- 1. Cleaning models necessitate a classification of the cleaning mechanism in order to be transferable to arbitrary flows.
- 2. The fundamental cleaning mechanisms are diffusive dissolution, cohesive separation, viscous shifting and adhesive detachment.
- 3. A cleaning model for pre-wetted, swellable soils is developed by extending and improving the computational model of Joppa et al. (2017), who use a transient boundary condition to account for the soil behaviour.
- 4. The approach decreases the calculation time by about three orders of magnitude compared to a conventional multiphase simulation.
- 5. The new model is solely based on fluid mechanics theories rather than empirical correlations, thus virtually applicable in arbitrary complex flows.
- 6. The model parameters can be determined in laboratory scale experiments.
- 7. The simulation's results show good agreement with experimental cleaning data.
- 8. Pre-wetted swellable soils tend to evolve a wavestructured surface enhancing the removal rate. This effect has to be included in future simulations.

#### NOMENCLATURE

Α	area, m <sup>2</sup>			
а	acceleration of the cleaning fluid, $m/s^2$			
$C_{sw}$	cleaning model parameter, 1/s			
C	concentration, $kg/m^3$			
D	diffusion coefficient, $m^2/s$			
Dt	turbulent diffusion coefficient, $m^2/s$			
$D^{*}$	swelling model parameter, $m^2/s$			
$D_{\rm h}$	hydraulic diameter, $D_{\rm h} = 4A/P$ , m			
I <sup>"</sup>	grey scale value, dimensionless			
Κ	consistency index, Pa s			
L	length, m			
$m_{\rm s}^{\prime\prime}$	surface soil coverage, kg/m <sup>2</sup>			
$\Delta m_{\rm s.pw}^{\prime\prime}$	soil mass removed by cohesive separation, $kg/m^2$			
ṁζ <sup>′′</sup>	soil removal rate, $kg/(m^2s)$			
ก้	flow behaviour index, dimensionless			
Р	wetted perimeter, m			
р	parameter at correcting <i>I</i> , dimensionless			
q	parameter at correcting <i>I</i> , dimensionless			
R	removal coefficient, kg/(m s)			
Rz	roughness, μm			
Re	Reynolds number, $Re = u_b D_h / v$ , dimensionless			
Т	time span, s			
t	time, s			
t <sub>90</sub>	time when ten percent of the initial soil remain, s			
t <sub>r</sub>	reptation time, s			
и	mean velocity, m/s			
у	wall normal coordinate, m			
$\Delta y^+$	dimensionless cell size, dimensionless			
α	cleaning model parameter, dimensionless			
$\beta^*$	swelling model parameter, dimensionless			
Ϋ́	shear rate, $s^{-1}$			
δ	half of the channel's height, m			
θ	temperature, °C			
ν	kinematic viscosity, m <sup>2</sup> /s			
τ	shear stress, Pa			
$ au_0$	yield stress, Pa			
ρ	density, kg/m <sup>3</sup>			
$ au_0$	yield stress, Pa			
Ø	mean volume fraction of soil, dimensionless			

 $\phi$  relative humidity, dimensionless

 $\Psi$  cleaning model parameter, dimensionless

## Subscript

0	initial
b	bulk
cor	corrected
d	decay
exp	experiment
max	temporal maximum
pw	pre-wetted
r	reptation
S	soil
SW	swelling
sim	simulation
t	turbulent
w	wall

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