

MONITORING OF THE LOCAL CLEANING EFFICIENCY OF PULSED FLOW CLEANING PROCEDURES

Martin Schöler¹, Tatjana Fuchs², Manuel Helbig¹, Wolfgang Augustin², Stephan Scholl² and Jens-Peter Majschak¹

¹ Technische Universität Dresden, Faculty of Mechanical Engineering, Institute of Processing Machines and Mobile Machines, 01062 Dresden, Germany, Tel:+49 351 46342273, Fax:+49 351 46337142, martin.schoeler@tu-dresden.de

² Technische Universität Braunschweig – Institute for Technology, Institute for Chemical and Thermal Process Engineering, Langer Kamp 7, 38106 Braunschweig, Germany, Tel:+49 531 3912789, Fax:+49 531 3912792, w.augustin@tu-braunschweig.de

ABSTRACT

A new measuring technique in combination with tailored CFD simulations was developed for monitoring the cleaning with pulsed flow of complex piping equipment. Investigations of pulsed flow cleaning published prior to this work focused on tests with straight pipes, whereas difficulties in industrial cleaning operations more often arise while operating piping systems and plant components with complex geometries. Therefore a new approach was necessary to investigate the cleaning process with the ability of monitoring the cleaning progress independent of both, time and place. Cleaning experiments were performed in a CIP test rig simulating industrial cleaning procedures. The optical monitoring procedure uses a model food soil consisting of starch as matrix material and phosphorescent crystals as optical tracer. Soil characterization, descriptions on test equipment as well as optical data analysis will be presented in detail. These tests are accompanied by CFD simulation with the commercial CFD software FLUENT using the same flow conditions and geometries. Unsteady flow conditions are introduced into the computational code by user defined functions and the results of these code modifications are presented.

INTRODUCTION

Cleaning procedures in food industry

The focus of the project presented is set on industrial cleaning in place (CIP) procedures in the food industry. Extensive work has been done in this field to shed a light on the parameters governing this processes. Though a huge number of scientific papers are available, a detailed explanation of all aspects important to understand cleaning processes is still missing due to the large number of parameters to be considered (Fryer, 2006). Consensus can be stated about the general factors of influence in cleaning procedures. For closed equipment, they can be described using the extended Sinner circle as a system dependent on six variables (Dürr, 2006). These are the kind and condition of the soil, the design of the plant as well as time, chemistry, mechanics and temperature as variables of the cleaning solution. Different models to describe cleaning processes are available as well, i. e. Jensen determined the

fluid mechanic part of this process as the governing one (Jensen, 2003). He also states that a minimal critical wall shear stress must be reached to yield a detectable cleaning effect. This observation is supported by the investigations of Timperley concerning the effect of Reynolds number and mean velocity on cleaning performance in turbulent pipe flows (Timperley, 1981). He reported a direct dependency of mean flow velocity and cleaning performance for different pipe diameters due to the decrease of laminar sublayer thickness with increasing flow velocity. Therefore he proposes the mean fluid velocity as an equivalent mechanical cleaning indicator instead of the Reynolds Number. As the laminar sublayer thickness converges to an asymptotic minimum value for velocities greater than 4 m/s, a further increase has been reported to yield only little improvement (Hoffmann, 1983). This assumption can be verified with calculating the laminar sublayer thickness with the logarithmic equation proposed by Schlichting and Gersten where the asymptotic behaviour is consistent to the previously named findings (Schlichting and Gersten, 2006). In contrast to this there are also theories which determine the diffusion processes as driving force in cleaning processes (Hofmann, 2007). Either way, fluid mechanics can promote both effects in a positive way, though it might not always be possible to differentiate which effect might be the governing one. Gillham for example investigated pulsed flow in terms of its cleaning potential focusing on concentration distribution of the detergents in the pipe (Gillham, 1997). The findings showed that pulsed flows do promote cleaning processes. However, it remains unclear, if this is due to the increase in wall shear stress magnitude and the changing of flow direction or the yielding of diffusion process adjacent to the flow direction because of transitional flow regimes.

It can therefore be assumed that (i) wall shear stress magnitude and (ii) diffusion processes do influence cleaning processes. Furthermore (iii) the application of transitional or turbulent flow regimes have the potential to support diffusion processes due to flow movements between the near wall region and the middle of the pipe. Finally (iv) the impossibility to differentiate between the different parameters governing cleaning must lead to a

critical evaluation of the monitoring methods applied to quantify cleaning procedures. Measured increases in wall shear stress for example do not necessarily lead to better cleaning results. A sole evaluation of these factors seems therefore not sufficient in every case.

With the objective of this project to reduce cleaning time and costs by the enhancement of cleaning mechanics, the application of flow types with an oscillating component seems to be the logic consequence.

Pulsed flow

The increase of the cleaning efficiency is playing a key role in improving food production. Higher efficiency leads both to improved hygiene conditions as well as to shorter downtimes and from there on to lower production costs. Ongoing research activities let assume that an increase of the cleaning efficiency can be obtained through the application of pulsed flows.

The present research project concentrates on gaining an in-depth knowledge of the variables influencing the cleaning process while utilizing pulsed flow regimes. The efficiency factor and the reach of the pulsation are of special interest. A holistic understanding of the pulsation effect under economical as well as constructional standpoints has to be established in order to develop methods for the optimal plant layout.

A pulsed flow is characterized by a stationary base flow, which is overlaid by an oscillating fluid movement w_{os} . For the description of the intensity of a superimposed pulsation the dimensionless waviness W as the quotient of the maximal oscillating and the basic flow velocity, is usually consulted.

$$W = \frac{w_{os,max}}{\bar{w}} \quad (1)$$

The mean velocity for an oscillation interval t_{os} is defined as

$$\bar{w} = \frac{1}{t_{os}} \int_0^{t_{os}} w(t) dt \quad \text{with}$$

$$w(t) = w_{stat} + w_{os} = w_{stat} + w_{os,max} \cdot \sin(\omega t) \quad (2)$$

According to theory (Dettmann, 1991) a waviness of $W > 1$ leads to a temporary flow reversal in the proximity of the wall as shown in Fig. 1. This increases the cleaning effectiveness significantly, which has been proven via experiments conducted by Bode (Bode, 2007). The graph in Fig. 2 states a huge drop in cleaning time when the $W = 1$ mark is approached and therefore supports the assumption made by Dettmann (1991).

A higher waviness leads to separation of the viscous sub layer and to the formation of eddies. This can decrease the thickness of the laminar sub layer at the surface when applying a turbulent flow. Furthermore, due to the variable ratio of inertial and frictional forces the ‘annular effect’ is characteristic for pulsating flow. Here the maximum velocity does not necessarily occur in the centre of the pipe, but can also occur near the wall, resulting in large shear rates and high wall shear stresses.

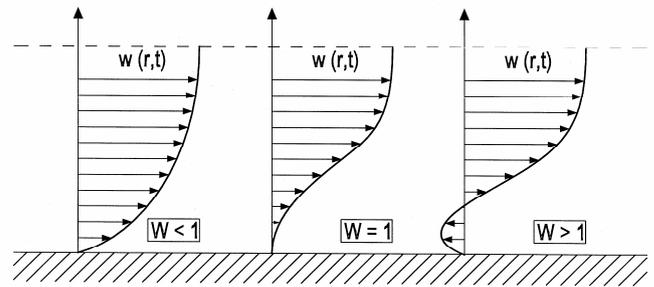


Fig. 1 Velocity profiles of pulsed flow for different waviness (Bode, 2007)

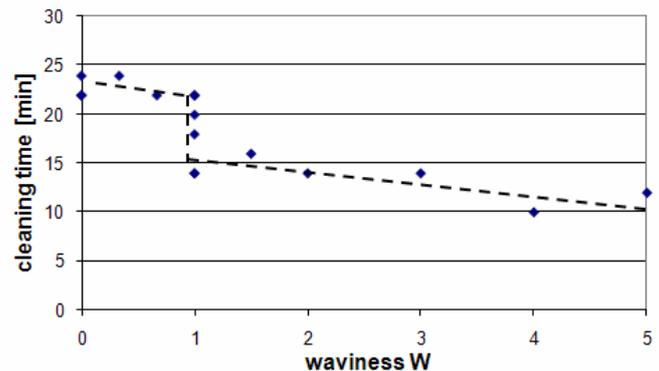


Fig. 2 Cleaning time versus waviness (Bode, 2007)

Flow velocity has a substantial influence on fouling behaviour (Krause, 1993). Higher velocities tend to break up the fouling layer much quicker due to an increase in shear stresses acting on the surface. A pulsed flow, as hypothesized, creates momentarily, high accelerations of the liquid flow around the fouling layer, thus can result in a decrease of removal time. The directional change of the liquid flow affects both the deposition rate, due to greater rates of mass transport rates, and removal of the fouling layer (Bohnet, 1987). Consequently during the cleaning process the mass transport of the cleaning agent to the deposit layer surface is enhanced. Experiments show that an up to 50 % shorter cleaning time is achievable when pulsed flow regimes are applied (Gillham, 1997; Bode, 2007).

CFD simulation of pulsed flows

So far in literature there are no simulation results for the cleaning process published, which consider the boundary layer for turbulent pulsed flows. Particularly the fluid dynamic elements which are used for the experiments demand a highly detailed modeling setup, since on the contrary to a straight pipe, separation and eddy effects must be taken into account.

The goal of CFD simulation is the reduction of the total effort required for testing and experimentation. Experimental findings can be complemented by simulations, but not to the point where they are totally expendable. At least to initially validate the CFD model's solutions, experimental data is needed.

The models necessarily needed for the numeric simulation, which are implemented into the CFD program

via user defined subroutines (UDS), are based on the following considerations. The flow parameters for fully developed, incompressible laminar flows can be determined via two quasi-analytic methods, which are based on (i) the Fourier series analysis and (ii) the Green functions (Celnik, 2006), with the help of the Navier Stokes equations. For the consideration of turbulent flows the widely used k- ϵ -model (Jensen, 2007) respectively similar models (Reynolds Averaged Navier Stokes - RANS) as well as locally resolved periodic calculations (Large Eddy simulation - LES) can be applied. The procedure for the simulation routine presents itself as follows: (a) loading of the mesh geometry, (b) activation of the solver for the computation of the flow equations, (c) entering of the physical parameters and boundary conditions, (d) activation of further models if necessary and (e) computation, presentation (post processing) and evaluation of the results. Special care has to be taken when it comes to parameter selection and fitting of the flow model as well as the local mesh generation and differentiation. Furthermore the definition of the transient boundary conditions at inlet and outlet via customized user-defined-subroutines is of great importance.

Scientific methods for the monitoring of cleaning

In current literature a multiplicity of methods to evaluate lab-scale cleaning procedures is available. A first classification can be made by the applied soil system. They divide in (i) the use of real food soils and (ii) model food soils. Attempts with real food soils, i.e. with practice-usual foodstuffs illustrate industrial practice very well. They are however least reproducible due to the often complex composition of the processed raw materials and therefore not discussed further. Model food soils, which consist usually of fats, proteins or carbohydrates mimic real material conditions quite sufficiently and are better reproducible due to their well-known composition.

A large number of cleaning protocols utilizing model food soils have been reported. Regarding the cleaning data derived from the protocols in question, three different approaches can be identified. These are (i) protocols measuring an integral value correspondent to cleaning with no information where the soil has been removed, (ii) cleaning protocols where cleaning information about a singular point of geometry is derived and (iii) those protocols that can detect a certain area of soiled geometry. Protocols according to group (i) have been reported for example by Gillham and Xin (Gillham, 2000; Xin, 2002). Both used pipe equipment soiled with whey protein and took samples of the cleaning detergent after the soiled test section. Gillham analysed these samples with the Bradford test, Xin with ultraviolet spectral photometry. This approach leads to characteristic cleaning curves quantifying the bulk material removed. These curves are of great interest if the balancing of cleaning kinetics in uniform equipment geometries is concerned.

Protocols of group (ii) either use sensors that are limited to point-wise detection like heat flux sensors or soiled specimens whose cleaning rate is evaluated integrally are applied (Bode, 2007). This can be done by dissolving

the soil left on the specimen and determining significant value like total organic carbon (TOC) for organic soils. Another method reported by Mauermann is the optical quantification of cleaning residuals left on the specimen after cleaning (Mauermann, 2009). Another method for point-wise soil detection was presented by Pereira with the so-called mechatronic surface sensor (Pereira, 2006). By inducing mechanical vibration into the specimen surface with a piezo element and recording the frequency response the thickness of the soil was calculated. For a known soil material, the method showed good agreement compared to measurements with a heat flux sensor.

Cleaning analysis of group (iii) is characterized by the application of model food soils and the evaluation of cleaning results with respect to equipment geometry. A method based on the removal of *Bacillus cereus* spores has been reported by Lelievre and was used in subsequent investigations by Bénézec and Blel (Lelièvre, 2002; Bénézec 2002; Blel, 2009). There the specimen are soiled in static conditions and cleaned in a CIP line. The quantification of remaining spores is done with the agar overlay technique. This method gives detailed information about the geometric distribution of the soil and can be used with a variety of pipe or equipment geometries. Hence the specimen has to be dismounted for evaluation, the test can only be performed at one point of time for one cleaning run and gives therefore only point-wise information about the cleaning progress. A method based on optical detection has been reported by Grashoff (Grashoff, 1983). To investigate circulation cleaning procedures he applied a whey protein soil of a known thickness to stainless steel sheets. He quantified the cleaning progress by mounting the sheets in a rectangular channel with the wall opposite the sheet made of glass and taking pictures of the residual left after certain time steps. The soil consisted of a protein layer and was deposited from a streaming protein solution on the heated test sheet. To enhance the optical contrast between the soil and the stainless steel sheet he added acridin orange, a fluorescent organic dye, to the soil matrix. To verify the findings derived from optical soil analysis the differential pressure loss over the soiled specimen was evaluated.

EXPERIMENTS

To specify the appropriate cleaning test method for this project a clear specification of the required features is necessary. These could be summarized as follows

1. Continuous geometrical detection of a pipe segment minimum 150 mm in length
2. Continuous time detection with free to choose time steps of data acquisition
3. Detectable pipe geometries must comprise straight pipes, sudden expansions, gradual expansions, sudden contractions and gradual contractions
4. Use of a model food soil and cleaning detergent appropriate to mimic food industry cleaning procedures
5. Test segment made of stainless steel common in food processing plants

As discussed previously, the exact combination of features to match these requirements has not been reported for a model food soil yet. Optical test methods seem to be the most promising approach hence they can utilize homogenous model food soil layers. Furthermore a large geometric array can be inspected. Therefore an optical method was chosen as basis for the experiments conducted during this work. In the first step, a specimen had to be designed enabling optical cleaning detection. This resulted in the test section shown in Fig. 3. It comprises a lower test section made of stainless steel (AISI 316) and an upper transparent test section made of PMMA (Polymethyl methacrylate). Both sections are equipped with lining grooves for frontal sealing, the upper test section additionally with a lining groove in axial direction.

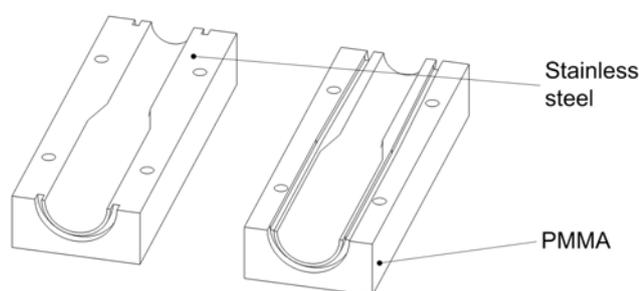


Fig. 3 Gradual expansion test sections

At the bottom region of the lower test section a model food soil is applied in a small stripe. The evaluation of only this fraction of the inner pipe geometry does not derogate the acquired test data as pipe flow can be assumed as axially symmetric. The mounted test section adds up to an inner pipe diameter of 26 mm. The length of the test section is 220 mm with a detectable length of 150 mm.

Model food soil application and detection

Methods like the one reported by Grasshoff, where the model food soil is build up by streaming a liquid solution over a heated surface, require a uniform wall-shear stress distribution at the whole specimen surface, if a homogeny build soil layer is needed. For optical test methods this is essential, as the thickness of the soil layer cannot be measured and must therefore be assumed as uniform. Given the non-uniform shape of the test sections used in this work, the deposition of fouling layers by streamed protein solutions cannot be used. Lang as well as Linderer reported an alternative method to soil flat specimen by using starch and a scraping module (Lang, 1991; Linderer, 1993). The agglutinated starch was put on the cleaned plate while a scraper removed the surplus material leaving behind a homogenous layer of known thickness. Subsequently the specimen was dried and heated following a certain protocol. This method does not require heating the specimen surface and it does not rely on fluid mechanic restrictions. Therefore this protocol of starch application combined with the optical detection method reported by Grasshoff build the basis of this work. First tests following the protocol of Lang (1991) for starch preparation showed good results

concerning the homogeneity of the soil but the optical contrast between starch and specimen was too small to guarantee accurate detection. To enhance optical contrast the use of colored dyes like iodide did not seem to be sufficient either. Similar to the work of Grasshoff fluorescent dyes were tested. Good results concerning homogenous distribution and handling were achieved with riboflavin, a dye also used for spray cleaning tests in industry. As this dye requires ultra violet activation like most organic fluorescent substances, problems occurred in combination with the upper test section made of PMMA, which absorbs ultra violet light. Furthermore riboflavin showed the tendency of dissolving in water out of the starch soil. Riboflavin was therefore rejected and replaced by crystalline zinc sulfide (Lumilux® Effect Green N-FF by Honeywell, USA). To obtain maximum optical contrast the phosphorescent effect of zinc sulphide is used which responds to excitation wave length in the visible spectra as well. Therefore the soil layer is activated with visible light for around 20 seconds. Subsequently the light source is switched off and the phosphorescent emission of zinc sulfide is detected with a camera while blocking off surrounding light with an appropriate housing. The zinc sulphide crystals used show a mean size of 20 micron with a maximum size of 80 micron in ordinary quality. To decrease the size distribution the crystals were fractioned to a size smaller than 40 micron. Due to the changed dye the starch formulation had to be altered too. Zinc sulfide crystals show a strong tendency of sedimentation in combination with agglutinated starch. Furthermore they tend to agglomerate. For this reason and to decrease preparation time the protocol was altered with respect to the method described by Rindlav-Westling (2003). Used was a soluble wheat starch (ordering code 13081, Grüssing, Germany) with an ash content of less than 0.7% and a pH of 6.0 to 7.5 (2%, water). For one soiling run 3 g starch are dissolved in 50 ml distilled water. The solution is then autoclaved at 121 °C for 20 min. Afterwards the solution is held at room temperature for around 8 h. Then 5 g zinc sulfide crystals are added and the suspension is stirred at 11000 rpm for 30 seconds (Ultra-Turrax, Ika-Werke, Germany). The application of the starch must not take more than ten minutes, otherwise the solution has to be stirred again to provide a homogenous distribution of zinc sulfide. The soiled test section is stored at standard laboratory environment for 24 h and dried afterwards for 2 h at 60 °C. As soon as the test section has reached room temperature again the cleaning test can be started. Several tests to determine starch composition have been undertaken such as fluorescence spectroscopy and scanning electron microscopy. Figure 4 shows a scanning electron micrograph of the applied soil matrix.

The picture illustrates the kind of distribution achievable with high-speed stirring, though the morphology of the starch matrix does not depict the real characteristics. At the moment of starch application, when the scraper removes the surplus material, a homogenous thickness is provided. It is therefore assumed that due to the application of high vacuum during the preparation of the specimen for scanning

electron microscopy the starch matrix decreases to a fraction of its former heights. To proof this assumption the preparation of scanning electron micrographs in liquid environment is planned.

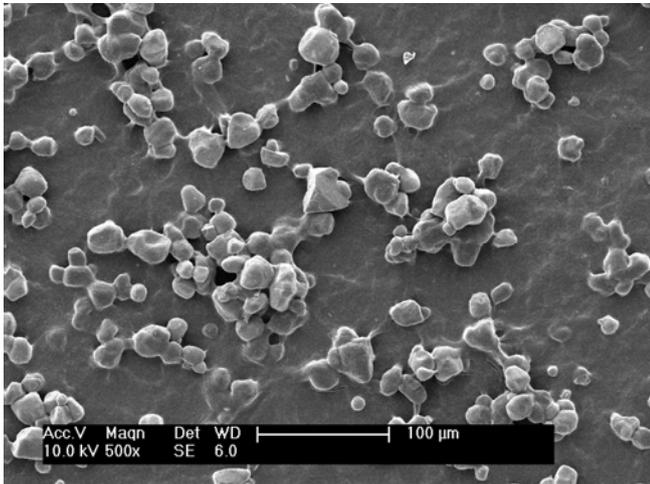


Fig. 4 SEM of starch zinc sulfide matrix on flat specimen

The application of the described soil matrix to the half-circular test sections used in this work is shown in Fig. 5.

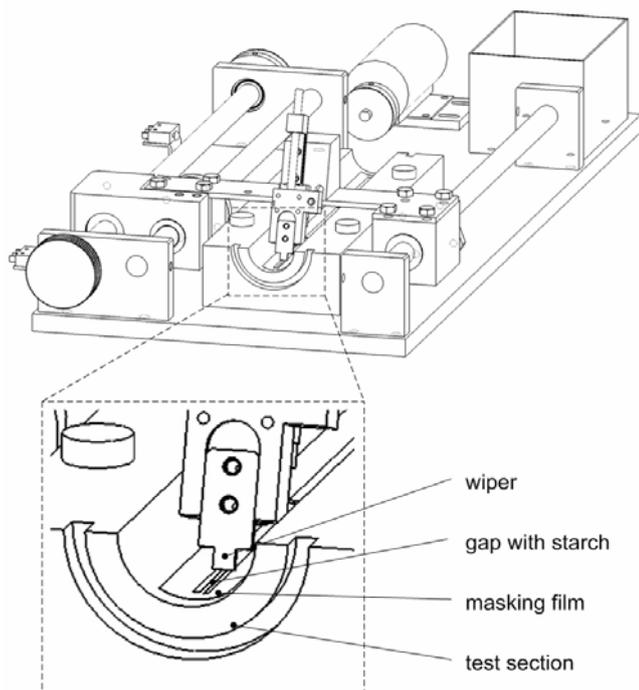


Fig. 5 Scraping module

The depicted scraping module comprises a ground plate where the lower test section is mounted. On the test section a PVC mask is applied. The mask consists of a film segment with a width of 13 mm and a length of 210 mm and a specific pattern of gaps forming two rows. The mask was made by a cutting plotter out of industrial self-adhesion foil (X-Film D-CU by modulator, Berlin, Germany). The scraping module furthermore comprises a wiper mounted

on a traverse which is moveable in the direction of the pipe axis and made of Polypropylene. The traverse is propelled by a small dc motor via a cograil.

To apply the modified starch matrix the test segment is cleaned with 2-Butanon (to remove residuals from the PVC mask), 2 % wt NaOH and 3 % wt HNO₃ manually. Then the PVC mask is fixed on the test segment. The starch zinc sulfide solution is then applied by hand on the mask. After activating the dc motor the wiper removes the unnecessary material from the segment. The PVC mask fulfills two tasks in that operation. First it guards the test segment surfaces against the wiper. Secondly it provides a margin of approx. 60 microns between the wiper and the surface of the test section. Given the flexibility of the wiper to adjust to different geometries of the test section, the thickness of soil matrix can be assumed as uniform throughout the test section with a thickness of around 60 μm in wet state and between 20 and 30 μm after drying. After the wiper has passed the whole length of the test segment the PVC mask is removed.

The final configuration of the optical test section is shown in Fig. 6. Depicted are the upper and lower test sections in profile with the flow direction in the picture plane. This monitoring setup further comprises a light source (two cold cathode fluorescence lamps, 11 W, color temperature 4000 K) and a CCD camera (Nikon D200) with a custom made optical lens (TSO Spezialoptik, Pulsnitz, Germany). The lamps activate the zinc sulfide for a duration of 20 seconds. Then lights are switched off and after a gap of one more second the picture is taken. Then the circle starts again. The section is equipped with a non-transparent housing to bloc surrounding light. Fig. 6 furthermore shows a schematic drawing of the applied starch-zinc sulfide matrix. The geometric relations between starch layer thickness and the particle size of zinc sulfide are not to scale.

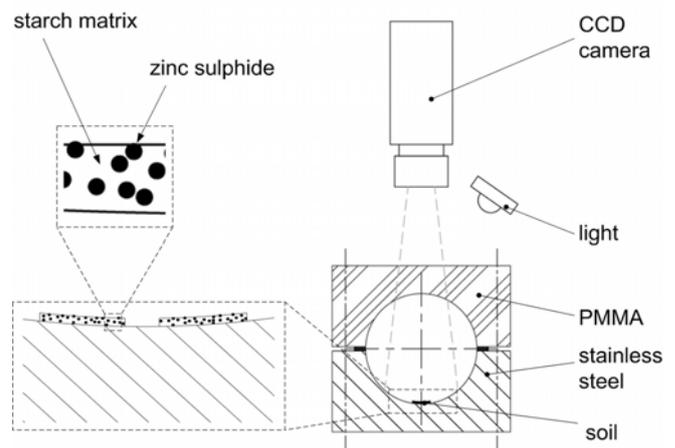


Fig. 6 Optical test section

Cleaning test rig

The test rig used in this work is set up as an open cleaning cycle. Fed by open reservoirs of water and cleaning agent (1 % wt NaOH solution) the cleaning solution is pumped through a candle filter (pore size 5 micron), the optical test section and back into the reservoir

(see Fig. 7). Before and after the test section straight pipes with a length of $\sim 60 L/D$ are mounted to provide sufficient establishment length. For later tests on pulsed flow cleaning a pulse generator can be added comprising a crankshaft drive powered by a 3 kW servo drive with adjustable crank length.

Water and cleaning solution are thermally in equilibrium with the whole test rig at around $25\text{ }^{\circ}\text{C}$ throughout the cleaning runs. The runs start with circulating water in the test rig for 2 minutes. Then NaOH (1 % wt solution) is pumped through the rig and the camera cycle is activated. The cleaning detergent circulates for a given time of around 80 minutes until the soil is completely removed from the specimen. Afterwards the rig is flushed with water for 2 minutes.

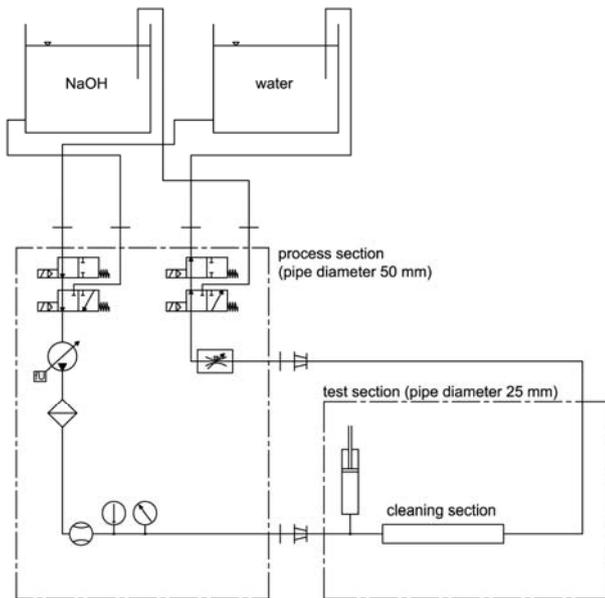


Fig. 7 Test rig

Imaging data analysis

The acquired images are processed using the software's ImageJ and MatLab. A scheme illustrating the analyzing process for one soil row is depicted in Fig. 8.

First, all files covering one cleaning run are cropped to a width (in y-axis) equivalent to 1 mm and a length (in x-axis) equaling 150 mm in reality. The cropped images are then converted from rgb true color into gray scale pictures using the `rgb2gray()` function provided by MatLab. This function converts rgb images by eliminating the hue and saturation information while retaining the luminance by means of forming a weighted sum of the different color components. Each pixel of the gray scale picture is then evaluated using a threshold function to get a picture consisting only of black (clean) and white (soiled) pixels. The border value used is chosen from empiric tests. The gaps in the soil rows in x-direction are identified by the software and the cleaning results are interpolated for those parts. Finally the mean value of all pixels in y-direction is calculated. The decision on which way of calculating should be used (harmonic mean value, RMS) has not been finalized yet.

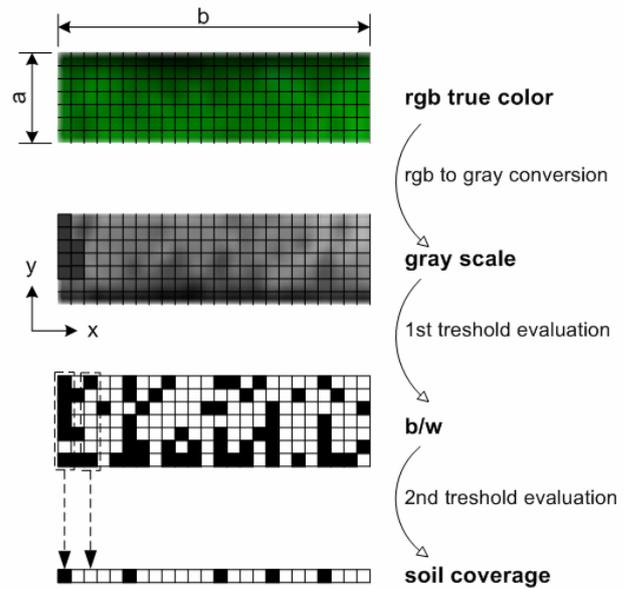


Fig. 8 Scheme on data analysing process

Data evaluation results in a $(1;n)$ matrix of soil coverage for one time step as shown in Fig. 8. For each point in x-direction, the timestamp is marked when the status "clean" is reached first. For all images, this result in a cleaning curve with the time required for soil removal drawn over the location at the test segment on x-axis.

For straight pipe segments the cleaning progress with respect to geometry can be assumed as homogenous. Therefore, the test results can be depicted in a different way to mark not only the passage of a certain cleaning threshold but the cleaning progress in time. This is possible if the average luminance emitted by the soil over the whole test module is plotted over cleaning time. Fig. 9 shows a graph where the cleaning of straight pipe test section (inner diameter 26 mm) has been investigated using steady fluid flow of 1 m/s. The depicted curve represents three independent cleaning runs with error bars showing the standard deviation. Indicated by the value of the error bars a good reproducibility can be assumed for the presented monitoring method.

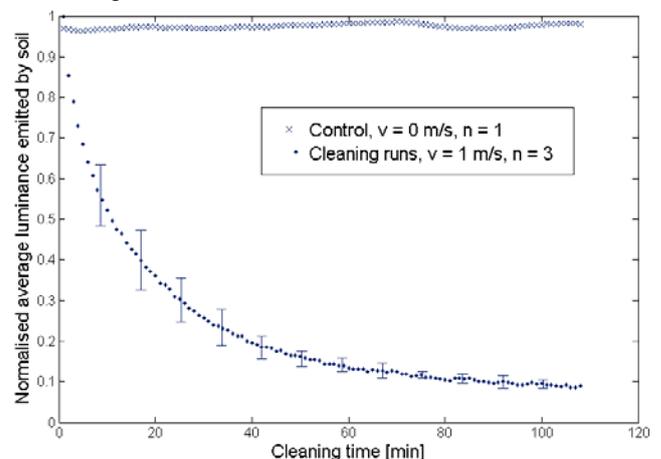


Fig. 9 Cleaning of three specimen with steady flow and one control with no flow

Nevertheless two additional series of tests were conducted. The first test was a cleaning run with the same setup as mentioned before but without fluid flow. The purpose was to investigate whether or not there is any chemical interaction between the zinc sulphide crystals and the sodium hydroxide solution that affects the detected luminance. As shown in Fig. 9 by the curve named 'Control', over a period of 120 minutes no interactions could be detected. The second test was done to compare the quantitative detection through the phosphorescence of zinc sulphide with other optical and gravymetrical methods. For that purpose the spray cleaning method presented by Mauermann (2009) was used. The soil matrix was applied to stainless steel plates (20 mm x 40 mm) and cleaned using a single spray jet that passes the specimen repetitively. The normalized average luminance detected with the zinc sulphide method was compared to the total dried weight of the soil and the area covered with starch measured after treating the starch with Lugol's iodine (Fig. 10). The number of cleaning cycles indicates how many times the spray jet has passed the specimen. The test was conducted for three stages (7, 11 and 14 cleaning cycles) and with three repetitions for each configuration. As indicated by the depicted error bars this second test too confirmed the good reproducibility of the zinc sulphide method compared to the technique presented by Mauermann.

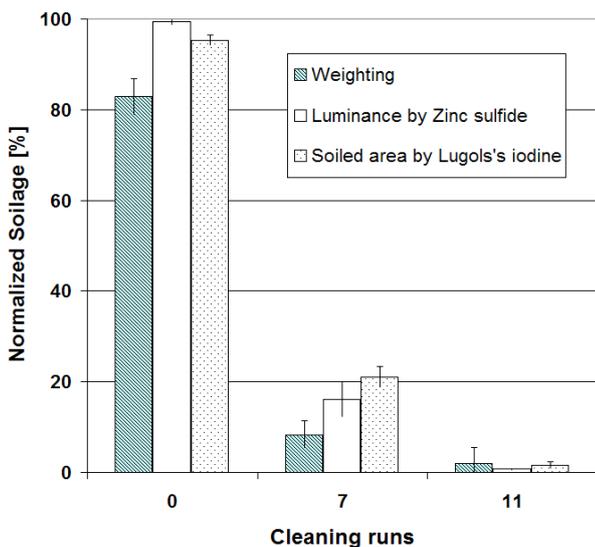


Fig. 10 Soil detected by three different methods on spray-cleaned flat stainless steel specimen with a zinc sulphide starch matrix

CFD simulation

This part of the research concentrates on the CFD simulation of flow regimes in basic geometries under different pulsed flow conditions. For this the CFD code FLUENT™ is used.

For a reliable CFD model the compilation of the calculation method is of great importance. Therefore a standardized method, which supplies plausible results, had to be developed. The configuration of the favored method takes place in three steps; (i) data preparation, (ii)

simulation, (iii) validation of the results. Whereat the results of the experiments described above are continuously aligned with the simulation to achieve the maximal accuracy. As result the CFD-simulation gives the time response of various parameters. The momentary velocity, velocity profiles along the tubes cross-section and the wall shear stress are considered the most significant ones.

For the first step of the method configuration, the preparation of the input data, great care has to be taken to determine the extent of the desired outcome precision and matching it with the available information on geometry, boundary and flow conditions. The degrees of freedom have to be limited in order to archive a manageable number of interactions. By calculating the Reynolds number it was ensured to operate in a turbulent flow regime ($Re > 25000$). The dimensions of the modeled geometries came from the segments tested during the soil experiments and were used to create mesh models utilizing the program Gambit™ which is Fluent's preprocessor. A mesh quality check as well as the introduction of boundary layers can be carried out with Gambit's analytic tools.

Before the simulation can be executed the mesh created with the preprocessor is loaded into the Fluent™ code and now the solver has to be configured. The fluent user's guide gives some clues how to choose the right settings. Besides physical models for example turbulence models and transport equations material properties can be uploaded from the Fluent™ database. Whereas the initial and boundary conditions have to be chosen according to the in the prior step prepared data. When the numerical model is set up, the computation and monitoring of the solution is started. The post processing is carried out with the tools Fluent™ provides.

In this project, first a steady state solution without pulsed flow has been calculated for each geometry. This convergent steady state solution was then implemented as the initial conditions for the unsteady case. To introduce the pulsation into the simulation setup functions were programmed using the programming language C++ which implicates a sinusoidal change of the inlet flow velocity.

The user defined function (UDF) has to be interpreted by Fluent and integrated into the boundary conditions of the inlet. After the initialization using the steady state solution the simulation is run again. Fluent provides various options for the solution visualization, for example the change of a flow profile over time can be animated or saved as pictures in variable intervals. Apart from this values of certain flow parameters can be logged in columns.

As shown in Fig. 11 those columns can easily turned into graphs. This way the shear stress on the test segments wall can be observed due to the use of situational tools, which can hardly be done in reality. One objective of these investigations is to find correlations between wall shear stress and the cleaning experiments.

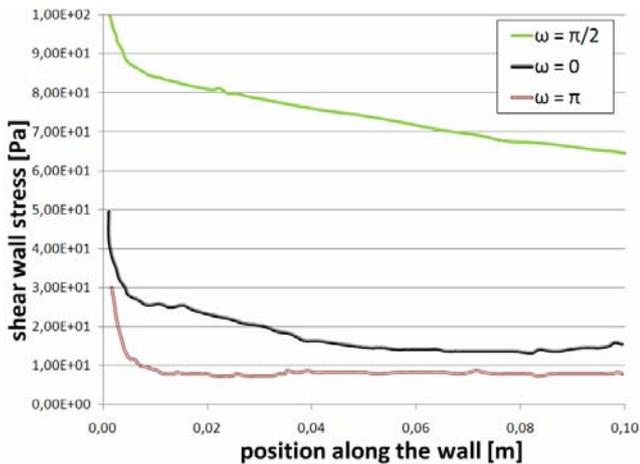


Fig. 11 Change of the shear wall stress over time, $W=1$

Fig. 12 shows flow profiles inside an elbow with a waviness of (a) $W = 0$ and $W = 1$ and a maximum velocity of 1 m/s.

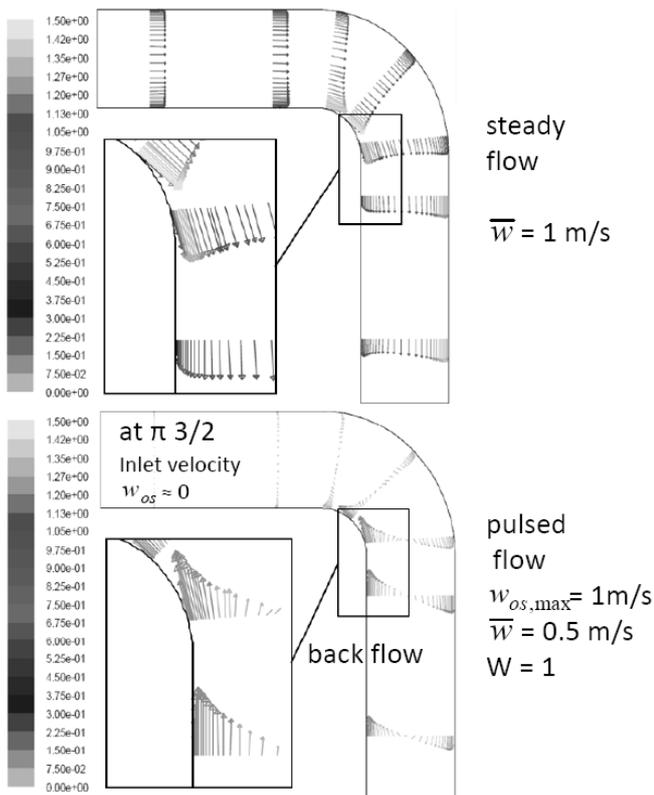


Fig. 12 Velocity profiles in an elbow

In the steady state simulation it is obvious that right after the bend on the inner wall the removal rate of a fouling layer is decreased due to low flow velocities. When the model is switched to pulsed flow the strongest back flow occurs exactly at this point. In simulations of geometries corresponding to the test segments used at TU Dresden (Fig. 3), similar results concerning velocity and shear wall stress were found. Areas where during the steady state flow low flow velocity and thereby low shear wall

stress dominate are highly influenced by pulsed flow conditions, which leads to an improved cleaning process. These results indicate that the investigation on the effect of pulsed flows is especially promising for more complex geometries than a straight pipe.

CONCLUSIONS

A new method for monitoring the cleaning of pipe segments with complex geometry has been presented. The possibility to investigate local cleaning phenomena of complex geometries like sudden expansions, gradual expansions, sudden contractions and gradual contractions has large potential for investigation of procedures like pulsed flow cleaning. Subsequent testing of the method will produce further data concerning the portability to industrial cleaning processes and the enhancement of the geometrical testing scope.

A customized method for the simulation of pulsed flow has been established. The integration of user defined function to imprint an oscillation on a former steady flow regime is successfully completed. The initial calculations show promising results concerning the feasibility of enhanced cleaning of complex geometries through pulsed flows.

In a next step CFD simulation of defined segments will be compared to the whey protein tests. The investigations will compare steady flow and pulsed flow cleaning results with the data derived from CFD simulations. The CFD simulation approach will accompany these studies, in order to refine and improve the chosen model and verify the outcome. Further studies will cover the same comparison concerning pulsed flow cleaning operations in more complex geometries.

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NOMENCLATURE

t	time, s
W	waviness, -
\bar{w}	mean oscillating velocity, m s^{-1}
w_{os}	oscillating velocity, m s^{-1}
$w_{os,max}$	maximum oscillating velocity, m s^{-1}
w_{stat}	steady flow fluid velocity, m s^{-1}
x	coordinate pipe axis, m
y	coordinate adjacent to pipe axis, m
a	picture dimension in x-axis, m
b	picture dimension in y-axis, m
L/D	Pipe length to pipe diameter ratio

REFERENCES

- Bénézech, T., Lelièvre, C., Membré, J.M., Viet, A.-F., Faille, C., 2002, A new test method for in-place cleanability of food processing equipment, *Journal of Food Engineering*, Vol. 54, pp. 7-15
- Blel, W., Gentil-Lelièvre, C. L., Bénézech, T., Legrand, J., Legentilhomme, P., 2009, Application of turbulent pulsating flows to the bacterial removal during a cleaning in place procedure. Part 1: Experimental analysis of wall shear stress in a cylindrical pipe, *Journal of Food Engineering*, Vol. 90, pp. 422 – 432
- Bode, K., Hooper, R. J., Augustin, W., Paterson, W. R., Wilson D. I., Scholl, S., 2007, Pulsed flow cleaning of whey protein fouling layers. *Heat Transfer Eng.*, Vol. 28, pp. 202 - 209
- Bohnet, M., 1987, Fouling of Heat Transfer Surfaces, *Chem. Eng. Technol.*, Vol. 10, pp. 113-125
- Celnik, M. S., Patel, M. J., Pore, M., Scott, F., and Wilson, D. I., 2006, Modelling laminar pulsed flow for the enhancement of cleaning, *Chemical Engineering Science*, Vol. 61, pp. 2079-2084
- Dettmann, P., 1991, Zusammenhang zwischen Geschwindigkeitsprofilen und Wärmeübergang bei turbulent pulsierender Rohrströmung, *Wärme- und Stoffübertragung*, Vol. 26, pp. 213-218
- Dürr, H., Graßhoff, A., Hofmann, J., Hufnagel, A. et al. (eds.), 2006, *Reinigung und Desinfektion in der Lebensmittelindustrie*. B. Behr's Verlag GmbH & Co. KG, Hamburg
- Fryer, P. J., Christian, G. K., Liu, W., 2006, How hygiene happens: physics and chemistry of cleaning. *International Journal of Dairy Technology*, Vol. 59, pp. 76-84
- Gillham, C. R., 1997, *Enhanced cleaning of surfaces fouled by whey proteins*, PhD thesis, University of Cambridge
- Gillham, C. R., Fryer, P. J., Hasting, A. P. M., Wilson D. I., 2000, Enhanced cleaning of whey protein soils using pulsed flows, *Journal of Food Engineering*, Vol. 46, pp. 199-209
- Hoffmann, W., 1983, *Zirkulationsreinigen von geraden Rohren in Abhängigkeit von Oberflächenrauheit und anderen Einflussfaktoren*, PhD Thesis, Universität Kiel
- Hofmann, J., 2007, *Stoffübergang bei der Reinigung als Qualifizierungsmethode der Reinigbarkeit*, PhD thesis, Technische Universität München
- Jensen, B. B., 2003, *Hygienic Design of Closed Processing Equipment by use of Computational Fluid Dynamics*, PhD thesis, Danish Technical University, Copenhagen
- Jensen, B. B., Stenby, M., Nielsen, D. F., 2007, Improving the cleaning effect by changing average velocity, *Trends in Food Science and Technology*, Vol. 18, pp. 52–63
- Krause, S., 1993, Fouling of heat transfer surfaces by crystallization and sedimentation. *Int. J. Chem. Eng.*, Vol. 33, pp. 357-403
- Lang, V., Linderer, M., Wildbrett, G., Stifter, I., 1991, Methode zur definierten Verschmutzung ebener Flächen mit Stärke. *Seifen Öle Fette Wachse*, Vol. 117, pp. 104-106
- Lelièvre, C., Legentilhomme, P., Gaucher, C., Legrand, J., Faille, C., Bénézech, T., 2002, Cleaning in place: effect of local wall shear stress variations on bacterial removal from stainless steel equipment, *Chemical Engineering Science*, Vol. 57, pp. 1287-1297
- Linderer, M., Wildbrett, G., 1993, Untersuchungen zum maschinellen Geschirrspülen, *Seifen Öle Fette Wachse*, Vol. 119, pp. 822-828
- Mauermann, M., Eschenhagen, U., Bley, T., Majschak, J.-P., 2009, Surface Modifications – Application Potential for the Reduction of Cleaning Costs in the Food processing Industry. *Trends in Food Science and Technology*, Vol. 20, pp. 8-15
- Pereira, A., Rosmaninho, R., Mendes, J., Melo, L.F., 2006, Monitoring deposit build-up using a novel mechatronic surface sensor (MMS), *Trans IChemE*, Vol. 84 (C4), pp. 366-370
- Rindlav-Westling, Å., Gatenholm, P., 2003, Surface Composition and Morphology of Starch, Amylose, and Amylopectin Films. *Biomacromolecules*, Vol. 4, pp. 166-172
- Schlichting, H., Gersten, K., 2006, *Grenzschichttheorie, 10th edition* Springer-Verlag, New York
- Timperley, D., 1981, The effect of reynolds number and mean velocity of flow on the cleaning-in-place of pipelines. In Hallstrom, B., Lund, D. B., and Tragardh, C. (Eds.), *Fundamentals and Applications of Surface Phenomena Associated with Fouling and Cleaning in Food Processing*, University of Lund, Sweden, pp. 402-412
- Xin, H., Chen, X. D., Özkan, N., 2002, Whey Protein-Based Gel as a Model Material for Studying Initial Cleaning Mechanisms of Milk Fouling. *Journal of Food Science*, Vol. 67, pp. 2702–2710