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MODELING AND VALIDATION OF THE MECHANISM OF PULSED FLOW CLEANING

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ABSTRACT

The enhancement of the cleaning efficiency of cleaning in place (CIP) systems is playing a key role in improving food production. Cleaning models based on CFD (Computational Fluid Dynamics) can be a tool, which enables to identify locations in a plant difficult to clean and enhance the cleaning efficiency by appropriate fluid dynamics, i.e. the application of transient flow.

A CFD cleaning model was developed which is based on the assumption of a mass transfer controlled cleaning process. The physical basis of the model is the analogy between heat and mass transfer. A validation of the cleaning mechanism, using experimental data of local cleaning times in several complex geometries with varied static and transient flow velocities was carried out. A modified waxy maize starch with phosphorescent tracers was used as model food soil. The received results show a good agreement between the measured and simulated cleaning times. The cleaning model is suitable for the calculation of the cleaning progress for all fouling systems, where the cleaning mechanism is mass transfer controlled. It is now possible to visualize the effect of complex pipe geometries or inappropriate hygienic design on the overall cleaning time. Especially in locations difficult to reach with steady flow, the application of pulsed flow shows a shorter cleaning time. Based on the presented new CFD model the local cleaning efficiency can be predicted.

Keywords: Food soil, cleaning, CIP, pulsed flow, mass transfer, CFD

INTRODUCTION

The cleaning of food processing equipment and machines is extremely important in hygienic and economic terms and provides further potential towards optimization. Higher efficiency leads to both, better hygienic conditions as well as shorter downtimes and, hence, to lower production costs. The objective of this work is to enhance the local cleaning efficiency using pulsed flow cleaning procedures. The present research project focuses on gaining an in-depth knowledge of parameters influencing the cleaning process while utilizing pulsed flow. The efficiency and the effective reach of the pulsation are of special interest.

Many scientific investigations have been carried out to identify the main parameters affecting the cleaning process, thus a huge number of scientific papers about this topic are available. At present, a detailed explanation of all aspects, important to understand cleaning mechanisms in industrial processes is still missing due to the large number to be considered [Fryer 2006]. Different models to describe cleaning mechanisms can be found in literature. Jensen (2003) specified a minimal critical wall shear stress that is required for a detectable cleaning effect. This view is supported by examinations of Timperley (1981), who described a direct dependency of mean flow velocity and cleaning performance for different pipe diameters and explained this by the decrease of the laminar sublayer thickness with increasing flow velocity. Instead of the Reynolds number he suggested the mean flow velocity as an appropriate mechanical indicator.

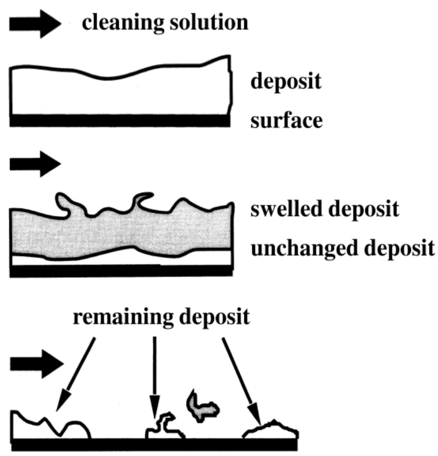

Fig. 1 Schematic steps during cleaning [Gillham 2000]

Gillham et al. (2000) described the cleaning process in three steps, as shown in Figure 1:

- diffusion of detergent into the fouling layer and swelling of deposit
- detaching of these gel-like structures and removing as aggregates by shearing action or dissolution
- removing of remaining swollen deposit by shear action of the fluid

A different approach is stated by Hofmann (2007) who described the mechanism in the cleaning process as mass transfer controlled. Gillham (1997) made investigations in pulsed flow with reference to the cleaning potential. The results showed an enhanced cleaning efficiency due to pulsed flow, but it was unclear, whether the major effect resulted from fluid dynamics (reversed flow, increased wall shear stress) or from mass transfer enhancement.

In the following work starch is used as model food soil, forming a cohesive fouling layer representing fouling type three [Fryer 2009]. In a first step the acting cleaning mechanism of the used type of fouling layer were determined. After this the potential of pulsed flow to enhance cleaning efficiency in CIP was examined.

Experiments

In prior work investigations of pulsed flow focused on tests with straight pipes [Bode 2007]. These experiments provided integral values of the cleaning efficiency, which cannot be transferred directly to more complex geometries with different local fouling and cleaning behavior. Therefore a novel optical measurement technique has been developed to investigate the cleaning process, called local phosphorescence detection method (LPD).

The soil used in this work consisted of a starch matrix containing phosphorescent zinc sulfide crystals with a mean diameter of 20 µm as optical tracer. To provide homogenous soil layers, the waxy maize starch was pre-gelatinized and acetylated. The test section consists of a horizontally splited pipe with a lower section made of stainless steel (AISI 316) and an upper transparent section made of PMMA (see Figure 2).

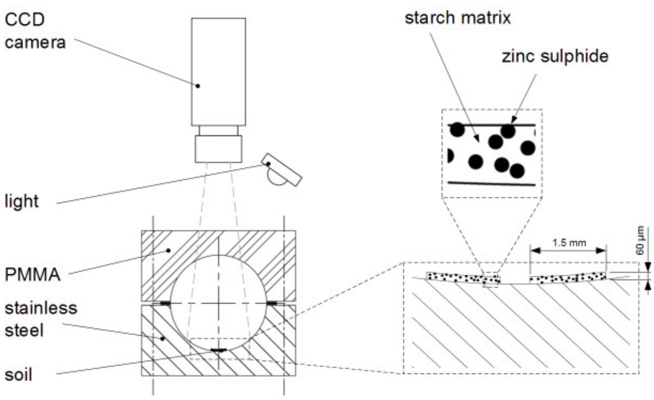

Fig. 2 Optical measurement device used in LPD

Two parallel stripes of the soil were applied evenly onto the lower section. During the cleaning experiment, the change of phosphorescence intensity was measured. To analyze cleaning , the Weibull model described by Dürr (2002) was used. Equation (1) shows the two-parameter Weibull distribution, wherein m_s/m_{s0} represents the normalized mass of the soil and t the elapsed cleaning time.

$$1-\frac{m_s}{m_{s0}}=1-e^{\left(\frac{t}{t_c}\right)^{r_c}} \qquad (1)$$

By linear regression t_c, the time needed to remove 63,2% of the initial soil, and r_c, slope of the Weibull curve, was calculated. More details are descibed in Schöler et al. (2011). Measurements in three different test sections (straight pipe with an inner diameter of 26 mm, sudden expansion with an inner diameter of 26 mm expanded to 38 mm, gradual expansion with an inner diameter of 26 mm expanded to 38 mm, pipe lengths of all pipes are 0,15 m) both with steady and pulsed flow were carried out. A mean velocity w in the smaller diameter between 1 m/s and 2.2 m/s, a waviness between 0.2 and 1.5 and a cleaning solution of 0.5 wt% NaOH were used in present study. This results in Reynolds numbers between 17,900 and 58,000. The setup of this local phosphorescence detection method is described in detail in Schöler et al. (2009).

A pulsed flow consists of a stationary base flow on which an oscillating fluid movement w_{os} is superimposed. The main parameter to characterize the pulsed flow is the waviness W, a dimensionless ratio of the maximum oscillating $w_{os,max}$ and the stationary or mean flow velocity.

$$W=\frac{w_{os,\max}}{\overline{w}} \qquad (2)$$

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

$$\overline{w}=\frac{1}{t_{os}}\int_0^{t_{os}} w(t)dt \qquad (3)$$

With

$$w(t)=w_{stat}+w_{os}=w_{stat}+w_{os,\max}\cdot\sin(\omega t) \qquad (4)$$

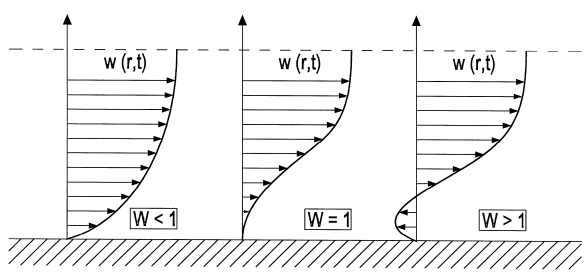

Fig. 3 Velocity profiles of pulsed flow for different waviness [Bode 2007]

According to theory [Schlichting 2006] a waviness of W > 1 leads to a temporary flow reversal in the proximity of the wall, referred to as the annular effect, as shown in Figure 3. A higher waviness leads to separation of the viscous sublayer and to the formation of eddies. This can decrease the thickness of the laminar sublayer 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 pulsed flow.

Simulation

No CFD model is known, which describes the cleaning process for complex geometries under turbulent and transient flow conditions. Based on experimental data which include a whole range of cleaning experiments at different flow conditions (detachment point, reattachment points, eddies, backflow etc.) like in complex plant geometries, a new cleaning model was developed. On the basis of previous work [Hofmann 2007] it can be assumed, that the wall shear stress is one but not the main parameter to characterize the cleaning progress for several food products.

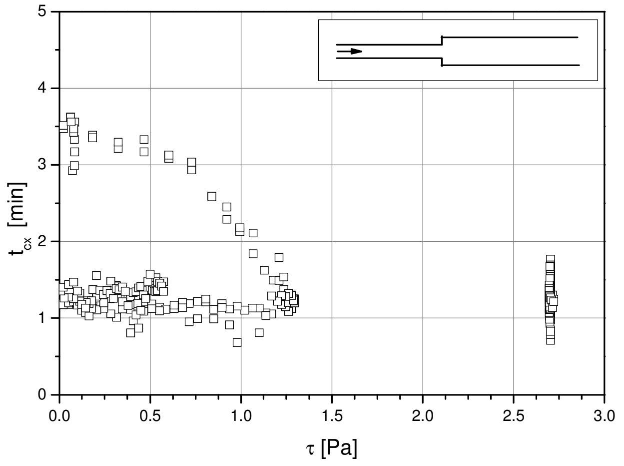

Fig. 4 Measured local cleaning time t_{cx} as a function of the simulated wall shear stress τ. Pipe with sudden expansion; w_{stat} = 1 m/s; Re = 26,000

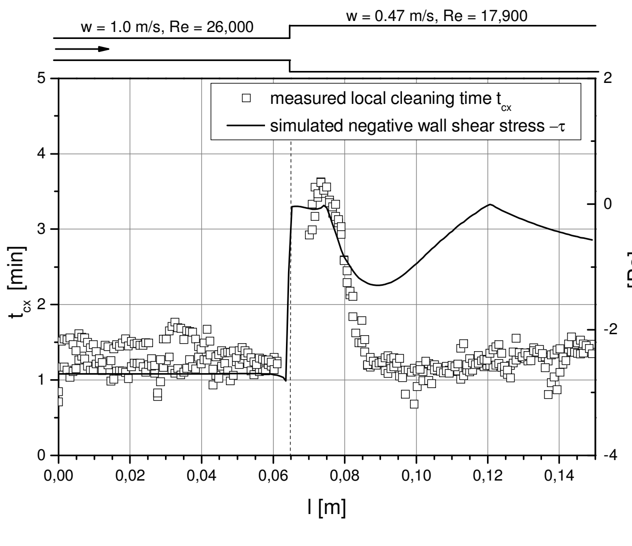

Fig. 5 Measured local cleaning time t_{cx} and simulated negative wall shear stress τ. Pipe with sudden expansion, inlet diameter 26 mm, outlet diameter 38 mm; w_{stat} = 1 m/s; Re = 26,000

Figure 4 and Figure 5 show that there is no unambiguous relation between the wall shear stress and local cleaning time for the soil used. With this knowledge a CFD cleaning model was developed, assuming a mass transfer controlled cleaning process. The physical basis of the model is the analogy between heat and mass transfer. It is based on a virtual temperature gradient between wall and fluid. Due to the temperature gradient and flow conditions different heat fluxes occur. It is quantified through the Nusselt number and may vary along the flow path due to axial changes in temperature gradients and flow conditions.

Based on the analogy observations the local heat transfer corresponds qualitatively to the mass transfer (Sherwood number) and furthermore for mass transfer controlled cleaning processes to the cleanability. The simulated Nusselt number is identical to the removal number Ã which is used further on, with the exception of characteristic length. The characteristic length is independent of the geometry and in each case equal to 1 m.

This implies

$$\tilde{A} = \frac{\alpha \cdot d}{\lambda} \tag{5}$$

with d = 1 m and is proportional to the Sherwood number (Nu ~ Ã ~ Sh). Furthermore the equation include the heat transfer coefficient α and the thermal conductivity λ. To reproduce the condition of mass transfer in this analogy it is important to correctly implement the boundary condition. During CIP it may be assumed, that there is no notable increase of the concentration of dissolved soil in the cleaning fluid in flow direction. Therefore the driving force, i.e. the concentration gradient between fouling layer and fluid, is constant and approximately equal to 1 mol L^{-1} m^{-1} for the system under investigation.

$$Driving\ \ force\ \hat{=}\ \frac{\partial c}{\partial x}\left[\frac{mol}{L \cdot m}\right] \approx 1 \tag{6}$$

To implement the described conditions to heat transfer, it has to be considered, that there is no notable increase of temperature in flow direction and therefore the driving force, here the temperature gradient, is constant in the whole fluid zone. For this, the temperature difference between wall and fluid has to be sufficiently small.

The following simulations were carried out using the software package ANSYS FLUENT 12.1. (finite volume discretization scheme). First of all a fluid dynamic validation resulted in the best turbulence model (k-ω-SST) and the appropriate mesh discretization for the expected fluid flow regime were carried out using the experimental data of Driver et al. (1985). The used mesh is unstructured tetrahedral mesh including structured boundary layers close to the wall ($y^+ < 1$). The simulation was done in a axisymmetric 2D model. The fluid inlet temperature is 300 K and the wall temperature 301 K, due to the small temperature difference the fluid properties are constant. The local heat transfer coefficient was calculated based on local flow field conditions (e.g. turbulence level, temperature, velocity profiles).

RESULTS & DISCUSSION

Comparison experiment vs. simulation for steady flow

At first a validation for steady flow conditions has been carried out. Figure 6 shows a comparison between measured cleaning time and simulated removal number $\tilde{A}$ at a flow velocity of 1 m/s in a sudden expansion. The cleaning time is constant in the smaller pipe section, which corresponds well with the constant removal number in this area. Behind the sudden step, there is a steep increase of the cleaning time due to a stagnation region. This corresponds with the simulated removal number. At last, the slight increase of the cleaning time at the end of the pipe due to decreased velocity in the wider diameter is in accordance with the simulated removal number.

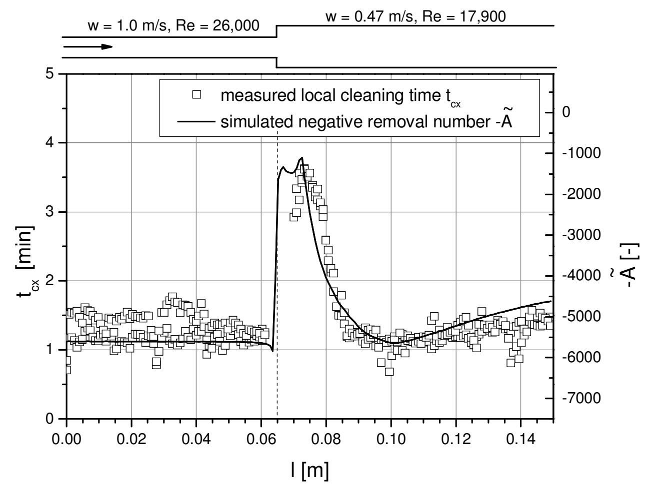

Fig. 6 Measured local cleaning time t_{cx} and simulated negative removal number $\tilde{A}$. Pipe with sudden expansion, inlet diameter 26 mm, outlet diameter 38 mm; w_{stat} = 1 m/s, Re = 26,000

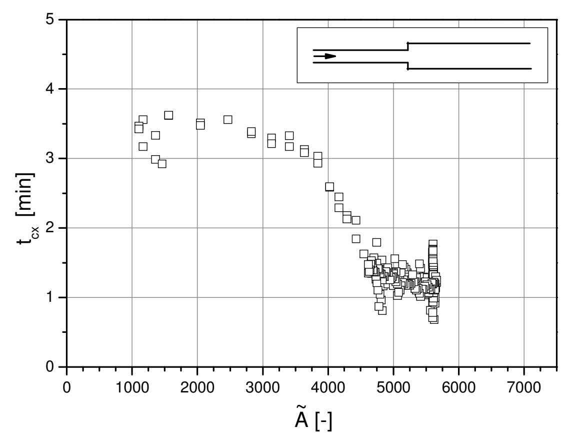

Fig. 7 Measured local cleaning time t_{cx} as a function of removal number $\tilde{A}$. Pipe with sudden expansion, inlet diameter 26 mm, outlet diameter 38 mm; w_{stat} = 1 m/s; Re = 26,000

Figure 7 shows the measured local cleaning time t_{cx} as a function of removal number $\tilde{A}$. A clear correlation between the local cleaning time t_{cx} and the removal number $\tilde{A}$ appears, in contradiction to Figure 4, where an ambiguous relation between the wall shear stress and several cleaning times was found.

Comparison experiment vs. simulation for pulsed flow

For pulsed flow the removal number is not constant. With regard to mass transfer as acting mechanism, only the consideration of the average over a complete pulsation period gives a reasonable benchmark for the cleanability. In contrast to a wall shear stress controlled cleaning mechanism, reverse flow and momentary maximum values are not playing the dominant role so that the average mass transfer coefficient (proportional to $\bar{\tilde{A}}$, the average removal number), resulting in the specific cleaning rate, is essential. In Figure 8 the comparison between experimental local cleaning time and the removal number averaged over the pipe length is shown for a sudden expansion at a steady flow velocity of 1 m/s and a waviness of 1.2.

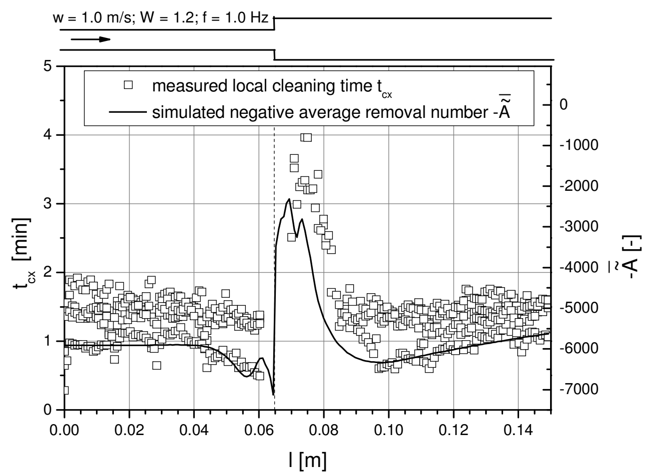

Fig. 8 Measured local cleaning time t_{cx} and simulated negative average removal number. Pipe with sudden expansion; w_{stat} = 1 m/s; Re_{stat} = 26,000; W = 1.2

The comparison shows a very good qualitative agreement of both values. The shorter cleaning time in the smaller pipe section close to the step corresponds well with the increased removal number in this area. Furthermore the slightly increased cleaning time at the end of the wider diameter due to a lower average velocity is in accordance with the simulated removal number. The qualitative progress of both values behind the step is the same. However the simulation predicts the cleanability to be better than the experiment shows. Reasons may be the difficult simulation of vortex areas and reattachment points, especially under pulsed flow conditions, as well as the scatter of the cleaning time at same positions (± 30 s) in the experiments. It is obvious, that under transient flow conditions the average of the removal rate gives an appropriate assessment of the cleanability. Therefore the approach of mass transfer controlled cleaning mechanism was confirmed and the general accuracy of the model was underlined. The validity of the cleaning model for steady and transient flow conditions in straight pipes and sudden expansions was proven. Even though the model gives no information about local and temporally viscous sublayer behavior due to pulsed flow (i.e. temporary changes in thickness due to reversed flow), it quantifies cleanability satisfactorily.

Cleaning Model

Based on the experimental and simulation results, a cleaning model was generated which enables to calculate the cleaning time of mass transfer controlled systems such as starch. A parameter study has been carried out with different geometries, different flow velocities with and without pulsation. Figure 9 shows the results of this study where each local cleaning time is corresponding to a removal number. In the range of high removal numbers there is low scattering which increases in direction of smaller removal numbers. Nevertheless a mathematical function was proposed including all data points as shown in the figure. Following this function it is now possible to calculate the local cleaning time based on the simulated removal number.

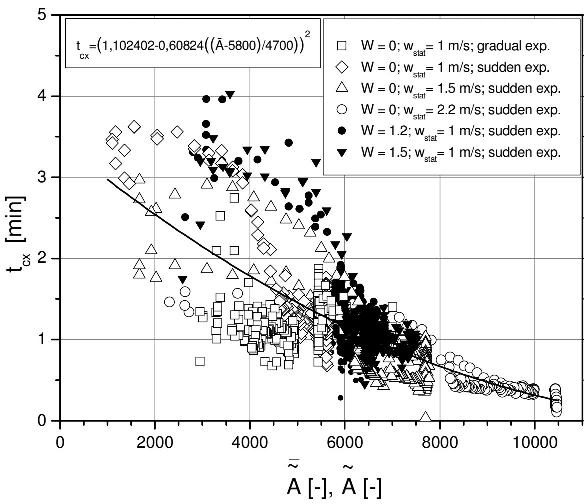

Fig. 9 Measured local cleaning time t_{cx} as a function of removal number Ã for all examined conditions

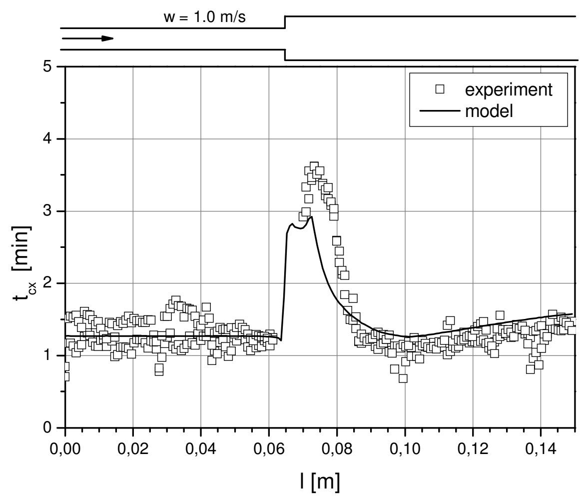

Fig. 10 Measured and calculated local cleaning times t_{cx}. Pipe with a sudden expansion; w_{stat} = 1 m/s; Re_{stat} = 26,000

Exemplarily, Figure 10 shows the comparison between experimentally determined and calculated cleaning times of a steady cleaning process with 1.0 m/s and Figure 11 of a transient cleaning process at a steady velocity of 1 m/s and a waviness of 1.2.

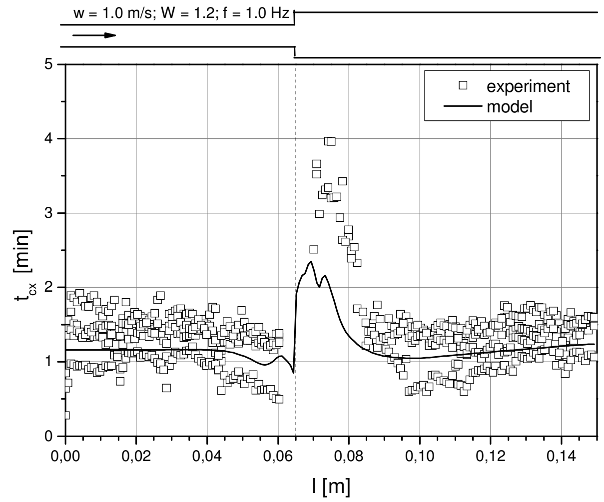

Fig. 11 Measured and calculated local cleaning times t_{cx}. Pipe with a sudden expansion; w_{stat} = 1 m/s; Re_{stat} = 26,000; W = 1.2

Influence of waviness

One main parameter characterizing a pulsed flow is the waviness W. As described above, a waviness W > 1 leads to a flow reversal in the boundary layer. Therefore the influence of the waviness on the total cleaning time t in straight pipes is experimentally examined, as shown in Figure 12. The black squares illustrate own results for the starch fouling layer and the white triangles show the results for whey protein fouling [Bode 2007].

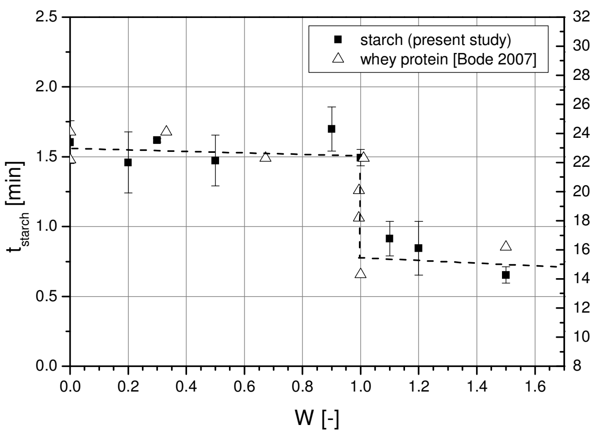

Fig. 12 Effect of waviness of pulsed flow on the cleaning time of starch and whey protein fouling [Bode 2007]

Both fouling systems follow the same characteristic course, but at a different time scale. The total cleaning time for 0 < W < 1 is nearly constant. At a waviness of W = 1 the cleaning time decreases suddenly. Due to the backflow, resulting in higher local flow velocities and thinner boundary layers, mass transfer is enhanced and leads to a decreased cleaning time. As described above, both fouling systems belong to fouling layer type three, which is characterized as a cohesive fouling layer [Fryer 2009] and obey the same mass transfer controlled cleaning mechanism.

Potential of pulsed flow in CIP

The total cleaning time is determined by the weakest link in the chain, i.e., the most difficult spot to clean in a plant. To optimize a cleaning in place process, to evaluate the potential of pulsed flow cleaning systems, a sudden expansion was examined more closely. There are easy to clean straight pipe elements and hard to clean locations behind the step due to stagnation regions.

Figure 13 shows the removal number at steady and transient flow conditions over an oscillation period at two different locations. Location ① is in the straight pipe region. During one oscillation period a temporally increase as well as decrease of mass transfer in comparison to steady flow conditions is found (full line [1] vs. dotted line [1] in upper diagram). To compare the cleaning with and without pulsed flow, the average removal number of both curves over one period have to be calculated. The result for pulsed flow is about 5% higher than without pulsation, which means there is a slightly better mass transfer. It is not necessary to optimize this region, because this is not the limiting factor. The worst place to clean, this means the place with the smallest average removal number received from the simulations, should be right behind the step in the area of the second location ②; for steady velocity this is at 0.073 m and for pulsed flow at 0.069 m. The comparison between steady and pulsed flow shows a better mass transfer during the whole period for pulsed flow (lines [2] in upper diagram). The enhancement of mass transfer is about 120%.

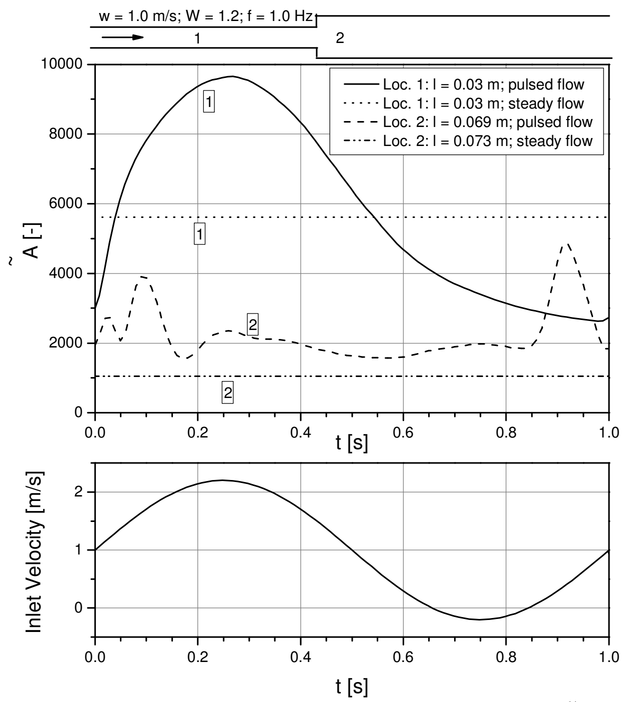

Fig. 13 Comparison of simulated removal number Ã with and without pulsed flow at two different locations in a pipe with a sudden expansion

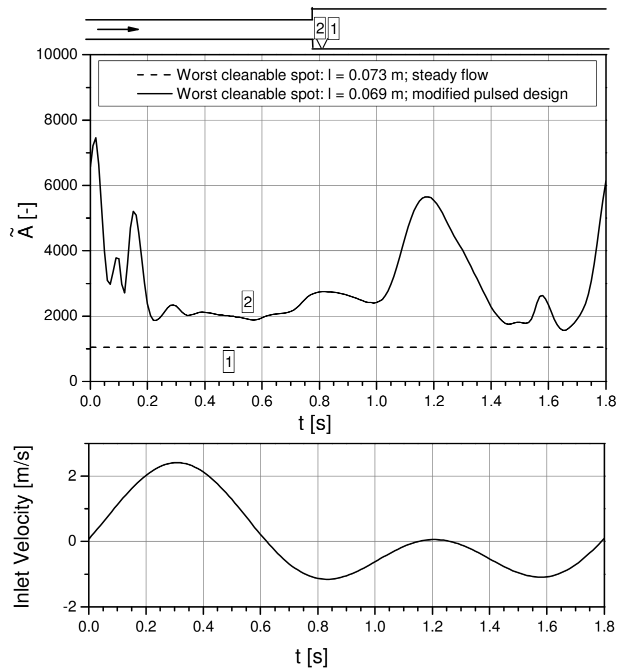

Fig. 14 Comparison of simulated removal number Ã with and without pulsed flow at the worst cleanable spot in a pipe with a sudden expansion

The modification of the velocity function is a promising approach to further enhance the cleaning efficiency. The lower diagram in Figure 14 shows a modified velocity function, the period takes 1.8 s, the maximum velocity is ~ 2.2 m/s and the minimum velocity ~ -1.1 m/s. To evaluate the cleaning result again the mass transfer at the worst cleanable spot is compared, i.e. the spot with the lowest average removal number over a period. For a steady velocity of 1 m/s (location 0.069 m) and for the new velocity function (location 0.073 m), the comparison is shown in Figure 14 on top. Again the mass transfer during the whole period is much better than in the steady case. Figure for the average removal number over one period for the new velocity function is 3,000, for the sinusoidal pulsed flow 2,200 and for steady flow 1,000.

CONCLUSION

It could be shown, that the application of pulsed flow in CIP leads to enhanced cleaning efficiency in straight pipes as well as in complex geometries with locations difficult to reach with steady flow. Furthermore the possibility to simulate a mass transfer controlled cleaning process using the analogy between heat and mass transfer was presented. The cleaning model appears suitable for the calculation of the qualitative cleaning progress for all mass transfer controlled fouling systems. A good agreement between the measured cleaning time t_{cx} and simulated removal number Ã for different complex geometries (sudden and gradual expansion) and transient flow regime was found. It is now possible to visualize the effect of complex pipe geometries or inappropriate hygienic design on the overall cleaning time. Based on the presented CFD model the local enhancement of the cleaning efficiency using pulsed flow can be predict. The adaption of the velocity function on existing plant geometries shows a promising possibility to enhance the cleaning efficiency. This approach is in focus for future investigation.

NOMENCLATURE

$\tilde{A}$	removal number, dimensionless
c	concentration, mol L^{-1}
d	characteristic length, m
f	frequency, s^{-1}
l	length, m
m_s/m_{s0}	normalized mass of soil, dimensionless
Nu	Nusselt number, dimensionless
Re	Reynolds number, dimensionless
r_c	Weibull cleaning characteristic, dimensionless
Sh	Sherwood number, dimensionless
t	time, s
W	waviness, dimensionless
w	velocity, m s^{-1}
α	heat transfer coefficient, W m^{-2} K^{-1}
λ	thermal conductivity W m^{-1} K^{-1}
τ	wall shear stress, Pa

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