Optimization of the cleaning efficiency by pulsed flow using an experimentally validated CFD model

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ABSTRACT

The enhancement of the cleaning efficiency of CIP systems is playing a key role in improving food production. Higher efficiency leads to both, better hygienic conditions as well as to shorter downtimes and, hence, to lower production costs. Cleaning models based on CFD can be a tool, which enable to identify locations in a plant difficult to clean and enhance the cleaning efficiency by appropriate fluid dynamics, i.e. the application of transient flows. The objective of this work is to enhance the local cleaning efficiency using pulsed flow. It was shown that this aim can be achieved through the application of transient flows [Bode 2007]. The present research project concentrates 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.

In this work, a CFD cleaning model was generated which is based on the assumption of a diffusion controlled cleaning process. The physical basis of the model is the analogy between heat and mass transfer. Several steps of validation with experimental data were carried out. A fluid dynamic validation resulted in the best turbulence model and the appropriate mesh discretization for the expected fluid flow regime. This was followed by a complex validation of the cleaning mechanism, using experimental data of local cleaning times in several complex geometries with varied static and transient flow velocities. A modified waxy maize starch with phosphorescent tracers is used as model food soil. The cleaning model is suitable for the calculation of the qualitative cleaning progress for all fouling systems, where the cleaning mechanism is diffusion controlled. The received results show a good agreement between the measured and simulated cleaning times for complex geometries and transient flow regime. 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 cleaning efficiency using pulsed flow can be predicted.

Keywords: Food soil, cleaning, CIP, pulsed flow, diffusion, CFD

INTRODUCTION

The cleaning of food processing equipment and machines is extremely important in hygienic and financial terms and provides further potential towards optimization. The enhancement of efficiency in CIP systems is playing a key role in improving food production. Cleaning models based on CFD can be a tool, which enable to identify locations in a plant difficult to clean and enhance the cleaning efficiency by appropriate fluid dynamics, i.e. the application of transient flows.

The objective of this work is to enhance the local cleaning efficiency using pulsed flow cleaning procedures. The present research project concentrates 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. In order to achieve these objectives, cleaning experiments with a diffusion controlled food soil model were carried out and a validated cleaning model was developed. Based on this, an in-depth examination of the potential of pulsed flow in CIP has been carried out.

Many scientific investigations have been done to find the main parameter 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 mechanism in industrial processes is still missing due to the large
number to be considered [Fryer 2006]. There are different models to describe cleaning mechanism found in literature. Jensen (2003) specified a minimal critical wall shear stress required for a detectable cleaning effect. This knowledge 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 laminar sublayer thickness with increasing flow velocity. Instead of the Reynolds number he suggested the mean flow velocity as an equivalent mechanical indicator.

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

- diffusion of detergent into 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 (2006) who describes the mechanism in cleaning process as diffusion 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 is unclear, whether the major effect results from fluid dynamics (reversed flow, increased wall shear stress) or from mass transfer enhancement.

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

**MATERIALS & METHODS**

The research project consists of two cross-linked parts, a simulation part where a cleaning model was generated and an experimental part for the validation of the model.

**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.

The soil used in this work consisted of a starch matrix containing phosphorescent zinc sulfide crystals as optical tracer. The test section is of a horizontal split pipe with a lower section made of AISI 316 stainless steel and an upper transparent section made of PMMA. Two parallel stripes of the fouling model system were applied onto the lower section. During the cleaning experiment, the change of light intensity was measured and from this measured value the cleaning time and dimensionless removal rate was calculated. Measurements in three different test sections (straight pipe, sudden expansion, gradual expansion) both with steady and pulsed flow were carried out. The setup of the monitoring device 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 \( (w_{os,\text{max}}) \) and the stationary or mean flow velocity .

\[
W = \frac{w_{os,\text{max}}}{w}
\]
The mean velocity $\bar{w}$ for an oscillation interval $t_{os}$ is defined as

$$\bar{w} = \frac{1}{t_{os}} \int_{0}^{t_{os}} w(t) \, dt$$

with

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

(2)

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 2. 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 pulsed flow. Here the temporary maximum velocity does not necessarily occur in the center of the pipe but near the wall.

**Simulation**

No CFD model could be found in literature, 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 2009] 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. Figure 3 shows that there is no unambiguous relation between the wall shear stress and local cleaning time for the materials used in this work.

With this knowledge a CFD cleaning model, assuming a diffusion-controlled cleaning process, was developed. 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 heat transfer occurs. It is quantified through the Nusselt number $Nu$ 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 $Sh$) and further to the cleanability. The simulated Nusselt number is identical to removal number $A$ which is used in further examinations and both are proportional to the Sherwood number ($Nu \equiv A \sim Sh$). 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 in flow direction there is no notable increase of the concentration of dissolved soil in the cleaning fluid. Therefore the driving force, i.e. the concentration gradient between fouling layer and fluid, is constant and approximately equal to $1 \text{ mol L}^{-1} \text{ m}^{-1}$ for the system under investigation.

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

(3)

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

Comparison experiment vs. simulation for steady flow
At first a validation for steady flow conditions has been carried out. Figure 4 (left) shows a comparison between measured cleaning time and simulated removal number $\bar{A}$ at 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. Figure 4 (right) shows the measured local cleaning time $t_{cx}$ as a function of removal number $\bar{A}$. A clear correlation between the local cleaning time $t_{cx}$ and the removal number $\bar{A}$ appears, in contradiction to Figure 2 where an ambiguous relation between the wall shear stress to several cleaning times is seen.

![Figure 4](image)

**Figure 4.** Comparison of measured local cleaning time $t_{cx}$ and simulated negative removal number $\bar{A}$ (left) and measured local cleaning time $t_{cx}$ as a function of removal number $\bar{A}$ (right) (cylindrical pipe with sudden expansion, inlet diameter of 26 mm, outlet diameter of 38 mm, steady flow velocity $w = 1$ m/s, $Re = 26,000$)

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 makes sense to benchmark the cleanability. In contrast to a wall shear stress controlled cleaning mechanism, reverse flow and momentary maximum values are not playing the dominant role. Only the average mass transfer coefficient (proportional to average removal number $\bar{A}$) resulting in the specific cleaning rate is essential. In Figure 5 the comparison between experimental local cleaning time and the removal number average 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. The comparison shows a very good qualitative as well as quantitative agreement between both values. The decreased 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 does. Reasons may be the difficult simulation of vortex areas and reattachment points, especially in pulsed condition, as well as the experimental part evident in the scatter of the cleaning time at same positions ($\pm$ 30 s). 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 diffusion controlled cleaning mechanism was confirmed and the general accuracy of the model was underlined. Thus 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 sub layer behavior due to pulsed flow (i.e. temporally changing in thickness due to reserved flow), it quantifies cleanability quite well.

![Figure 5](image)
Advantages of pulsed flow in CIP

To optimize a cleaning in place process, 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 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 places behind the step due to stagnation regions.

Figure 6 shows in each case 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 an oscillation period, a temporally increase as well as temporally decrease of mass transfer in comparison to steady flow conditions is found. To compare the cleaning with and without pulsed flow, both curves have to be integrated over one period. The value using pulsed flow is a bit higher than without pulsation, which means there is a slightly better mass transfer. It is not necessary to optimize this region with regard to the cleaning time, because this is not the limiting factor. The second location 2, right behind the step, should be the worst place to clean. The comparison between steady and pulsed flow shows a better mass transfer during the whole period for pulsed flow. Hence, the total cleaning time for this typical configuration could be reduced.

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_cx in straight pipes is experimentally examined, see Figure 7. The black squares illustrate the own results of a starch fouling layer and the white triangles show the results of whey protein fouling [Bode 2007]. Both fouling systems follow the same characteristic course. 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 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 described in literature as cohesive fouling layer [Fryer 2009] and obey the same cleaning mechanism (diffusion controlled).

CONCLUSION

It was 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 the diffusion controlled cleaning process using the analogy between heat and mass transfer was shown. The cleaning model appears suitable for the calculation of the qualitative cleaning progress for all fouling systems, where the cleaning mechanism is diffusion controlled. A good agreement between the measured cleaning time $t_{cx}$ and simulated removal number $\tilde{A}$ for complex geometries and transient flow regime is 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 new CFD model it is now possible to predict the local enhancement of the cleaning efficiency using pulsed flow. A parameter of special interest is the generation of the pulsed flow; non-sinus-shaped pulsations are in focus of future investigation.

Nomenclature

$\tilde{A}$ removal number  
$c$ concentration, mol L$^{-1}$  
$f$ frequency, s$^{-1}$  
l length, m  
$Nu$ Nusselt number  
$Re$ Reynolds number  
$Sh$ Sherwood number  
$t$ time, s  
$\tau$ wall shear stress, Pa  
$W$ waviness  
w velocity, m s$^{-1}$

REFERENCES


