Cleanability study of a scraped surface heat exchanger
BLEL Walid a(1), LEGENTILHOMME Patrick a, BENEZECH Thierry b and FAYOLLE Francine a

a GEPEA- UMR CNRS 6144, Saint- Nazaire, France (patrick.legentilhomme@univ-nantes.fr; francine.fayolle@oniris-nantes.fr)
b INRA UR 638, Villeneuve d’Ascq, France (thierry.benezech@lille.inra.fr)
(1) Present address: LIMAT B - EA 4250, Pontivy, France (Walid.Blel@univ-ubs.fr)

ABSTRACT
Scraped Surface Heat Exchangers (SSHE) are widely used industrially for treating food products with high viscosity (cheese, ice cream…). In this kind of heat exchangers, the presence of spinning blades allows a regular renewal of the product surface, preventing clogging and improving heat transfer. However, if the body of the heat exchanger is relatively easy to clean, the entry and the exit of SSHE are poorly cleanable due to their particular geometry and the presence of seals which make cleaning difficult. A specific study was conducted in the entry bowl of a SSHE, whose design has been optimized by the manufacturer in order to minimize the risk of deposit eliminating the hydrodynamical dead zones. The main goal of this study is to extend the correlation previously identified on simple systems between the wall velocity gradient and the cleaning ability to optimize the hydrodynamic conditions leading to efficient cleanability.

For this purpose, measurements of wall shear stress were made using the electrochemical method on the one hand, for different hydrodynamic conditions and especially in the presence of a pulsating flow. On the other hand, cleanability measurements after microbiological fouling and cleaning were performed. Two types of contamination were tested: spore-forming bacteria and biofilm. The clean in place protocol (0.5% NaOH, 60° C, 10 min.) is deliberately low in order to compare the different areas and allow an effective numbering of the colonies after culture. It follows that the geometry of the bowl tested presents no dead zones. However, the available space for flow significantly reduces the Reynolds number and turbulence intensity, which induces three areas of increasing contamination, corresponding to conditions of mean shears and low fluctuations. The use of a pulsating flow increases these fluctuations, and thereby reduces the residual contamination.

Keywords: cleanability; scraped surface heat exchanger (SSHE); flow; biofilm

INTRODUCTION
The cleaning and disinfecting of food processing equipment are very common and costly in terms of time and cleaning products. Despite progress in the field of cleaning closed surfaces, this operation is still difficult for some pieces of equipment having specific geometry, which results in serious health risks due to the contamination of manufactured products by the equipment itself. Scraped Surface Heat Exchangers (SSHE) belong to this range of equipment presenting such a specific geometry. They are widely used industrially for the processing of food products with high viscosity (cheese, ice cream, ...). However, their complex geometry and the presence of seals at the shaft of rotation make cleaning difficult. Previous studies [1,2] have confirmed by numerical simulations validated by PIV, that the flow in the core part of the heat exchanger is turbulent and promotes the dropout of any deposits. However, in the entrance area, a classical geometry of the bowl exhibits dead zones whatever the operating conditions used. This is why the Alfalaval company chose to develop an innovative geometry of the entry and exit areas in order to minimize these dead zones. Meanwhile, it emerged for simple geometries [3, 4] that it was possible to correlate the wall velocity gradient and cleanability. These works have also highlighted the contribution of the fluctuating value of the wall shear, in addition to the average value in the wrenching of spores adhering to the wall of tested devices. The beneficial role of fluctuations in wall shear rate on cleaning was used to test other types of unsteady flows such as the pulsating flow. Some work on straight pipes [5, 6] showed that the pulsed flows in a turbulent regime allow an increase of mean and fluctuating shear rates and a subsequent improvement of the kinetics of cleaning of spores. The effect of this type of flow on the pullout of biofilms adhering to the input of an SSHE is analyzed in the present study.
The aim of our work is to study specifically the entrance area of a SSHE to extend the correlation between wall shear forces and cleanability, identified previously on simple systems and then optimize hydraulic conditions leading to an efficient cleaning. At this level, tests with pulsed turbulent flows with different frequencies and amplitudes of pulsation are carried out to verify the effect of unsteady flows on complex geometries cleanability.

MATERIALS & METHODS

1- Scraped surface heat exchanger and tested flow

Figure 1 shows a simplified diagram of the Scraped Surface Heat Exchanger (SSHE) from Alfalaval used in the present study.

![Figure 1: Schematic diagram of the studied Scraped Surface Heat Exchanger (SSHE).](image)

The wall velocity gradients are measured using electrochemical sensors constructed from platinum wires flush-mounted into the risky areas of the entry bowl to be flush with the flow at the level of risk areas (Figure 2). Given the influence of the wall viscous sublayer on the accuracy of electrochemical measurements in terms of fluctuations [7], two probe diameters were used: probes 400 µm in diameter which have the advantage to allow a good precision on the fluctuating value of the shear wall and probes 1 mm in diameter, which in turn provide better accuracy on the mean shear rate value. The pulsations of the flow are generated by a solenoid system that can provide high pulse amplitudes and frequencies while maintaining a turbulent flow regime [5, 6]. This system allows an harmonic variation of the pulsed flow between a minimum and a maximum value at a given pulsation frequency. The conditions tested in this study, including in this order [minimum flow (L h\(^{-1}\)) - maximum flow (L h\(^{-1}\)) - Pulse frequency (Hz)] are the following: condition “a” [600 L h\(^{-1}\) - 2200 L h\(^{-1}\) - 2.5 Hz] and condition “b” [300 L h\(^{-1}\) - 1500 L h\(^{-1}\) - 2.5 Hz] for pulsed flow and two flow-rates in steady flow (2200 L h\(^{-1}\) and 3720 L h\(^{-1}\)). These flow conditions have been applied for both types of tests (measurement of wall friction and analysis of cleanability).

2- Cleaning in place procedure

The determination of residual contamination is done by cleaning up the circuit previously infected. This contamination occurs under dynamic conditions to be closer to real conditions of contamination of food production lines. Two types of contamination were tested, the first one to study the adhesion of bacterial spores on the surface of the heat exchanger, the second for the analysis concerning the appearing and the growth of biofilms on the investigated surface. In the first case, the contamination is made with milk containing spore-forming bacteria at a concentration of \(10^4\) UFC mL\(^{-1}\). This milk is circulated throughout the system during one hour. The formation of bacterial biofilms is, in turn, obtained from the circulation, during three days, of milk contaminated with the bacteria *Bacillus cereus* \((10^5\) UFC mL\(^{-1}\)) with a renewal of the contaminating solution each day.

The cleaning process takes place under “mild” conditions in order to keep a residual contamination that would demonstrate the effect of geometry and flow on the cleanability of the equipment. The cleaning in place is done using sodium hydroxide (0.5% w / w) for 10 min at 60° C. The flow conditions, stationary and pulsed, are applied to this level of cleaning. A prewash phase for 5 min with a flow rate of 300 L h\(^{-1}\) is applied before and after this step. The detection of residual contamination has been carried out through the casting method with nutrient agar containing triphenyletriazolium chloride [8, 9]. Small colonies appear in red, easy to distinguish from each other and directly accountable at the agar surface. This method allows localizing and quantifying the residual contamination of the heat exchanger.
3- Measurement of the wall velocity gradients

The measurement of wall velocity gradients is performed by an electrochemical method, the principle of which has been widely addressed in the literature and will not be developed here [3, 5]. This method allows the experimental determination of the liquid-solid mass transfer coefficient which, by analogy with momentum transfer, can be used to obtain the wall velocity gradient [10].

The electrochemical solution used is a mixture of potassium ferricyanide \((3 \times 10^{-3} \text{ mol L}^{-1})\), potassium ferrocyanide \((5 \times 10^{-2} \text{ mol L}^{-1})\) and sodium hydroxide \((0.5 \text{ mol L}^{-1})\) used as support electrolyte. To maintain the same flow regimes that when testing contamination and cleaning, flow-rates have been recalculated taking into account the physical characteristics of the cleaning solution (density = \(1028 \text{ kg m}^{-3}\) and viscosity = \(0.985 \times 10^{-3} \text{ Pa.s at } 22^\circ\text{C}\)). For a temperature of \(22^\circ\text{C}\), the diffusion coefficient of ferricyanide ions in the solution is equal to \(3.65 \times 10^{-10} \text{ m}^2\text{ s}^{-1}\). Obtaining the wall velocity gradient from the diffusional limiting current distribution is done by applying the analytical solution of Sobolik et al. [11], which consists in a correction of the quasi-stationary solution (QSS), considered as invalid for unsteady flows with high frequency fluctuations. The mean shear rate multiplied by the viscosity of the fluid yields the mean wall shear stress, \(\tau_w\), which will be presented. Figure 2 presents the shape of the inlet bowl as well as the microprobes positions.

![Figure 2: position of the electrochemical microprobes](image)

**RESULTS & DISCUSSION**

The electrochemical measurements were made in different zones of the entrance bowl of the heat exchanger. The results shown in figure 3 describe the evolution of the mean local shear stress. They also allow a comparison between the two flow conditions, steady flow of 2200 L h\(^{-1}\) and pulsed flow \([300 \text{ L h}^{-1} - 1500 \text{ L h}^{-1} - 2.5 \text{ Hz}]\). This condition is characterized by the set-up of a recirculation zone at the center core characterized by velocities in the opposite direction of the main flow. This last point emphasizes the effect of the pulsations on the mean shear stress values.

Works already done on straight lengths [5] have shown the beneficial effect of pulsations on the mean and fluctuating wall shear stress. Figure 3 shows that, despite an average Reynolds number in the presence of pulsations significantly lower than that corresponding to the stationary condition \((10,500 \text{ and } 25,500 \text{ respectively for pulsed flow condition and steady state one, calculated for a diameter equal to } 4.7 \times 10^{-2} \text{ m})\), the average stress values are very close, even greater, according to the positions of measurement, in pulsated condition. This result confirms the observations of Blel et al. [5] on straight pipes and shows that even for more complex geometries, the effect of pulsations is not limited to the flow core but is still dominant near the wall. We also notice a similar evolution of the mean shear stress with the same profile for both flow conditions tested. Thus, the pulsations applied to the flow only act on the magnitude of shear forces and do not alter the distribution of these forces near the wall. This result can be explained by the homogeneity of pulsation cycles (same frequency and amplitude) during the measurement period. The same remark can be made regarding the further condition of pulsation \([600 \text{ L h}^{-1} - 2200 \text{ L h}^{-1} - 2.5 \text{ Hz}]\): Figure 4 shows the rate of increase (%) of the mean shear stress with pulsations compared that obtained in steady state. However, unlike for straight pipes, this improvement depends on the measurement position and therefore the geometry available to the flow. Indeed, figure 4 shows that the effect of pulsations is greater on the closed surfaces...
where the flow is limited by the walls of the geometry. Further trials are planned to study the effect of cycles of heterogeneous parameters of pulsations (amplitude and frequency) on the improvement of the mean shear stress.

![Graphs showing the evolution of the mean shear stress for different locations in the inlet bowl.](image)

**Figure 3:** Evolution of the mean shear stress for different locations in the inlet bowl. Comparison between steady state flow and pulsed one.

Regarding the evolution of local wall shear stress, the line of electrochemical probes following the direction of the flow (probes 1-12 in figure 2) presents a significant variation between maximum and minimum values. Probe 1, located in the tubular part of the entry bowl, exhibits the greatest wall shear stress value. The decrease observed for the following probes can be explained by the opening of the flow section. The curvature of the geometry at the end of this line explains the increase of the shear stress for probes 11 and 12. Indeed, the flow which tends to follow a straight path should move towards the outside of the bend under the effect of centrifugal forces. This results in larger friction velocities on the outside part of the bowl. The same assumption can explain the increase of the mean shear stress on probe 18 with respect to other sensors (13, 14, 15, 16 and 17).

Observation of the stress values measured on the probes 19-27 shows an asymmetric flow due to centrifugal forces from the curvature. Indeed, the simultaneous analysis of the location of the probes in the bowl and the shear stress showed a low value on the row of sensors corresponds to a high shear stress on radially opposite probes, confirming the conservation of momentum in the flow section. This entire tubular portion of the entrance bowl presents a good cleanability level, especially using pulsation condition [300 L h\(^{-1}\) - 1500 L h\(^{-1}\) - 2.5 Hz]. Instead, the flat part of the entry bowl appears less cleanable.
Figure 4: Mean shear stress increase for the pulsating condition \([600 \, \text{L} \, \text{h}^{-1} - 2200 \, \text{L} \, \text{h}^{-1} - 2.5 \, \text{Hz}]\) compared with the steady state flow.

Figure 5 shows the colonies of *Bacillus cereus* spreading over the entire surface of the bowl. Low shear stress values can explain this result (probes 29-38). The comparison between the two flow conditions presented in figure 4 (a and b) shows a better cleanability using a pulsating flow, although very similar mean shear stress values are observed. Indeed, figure 3a shows a less dense distribution of colonies. This result is explained by the effect of pulsations on the fluctuating value of the shear stress that has already been highlighted in a previous study [5,6].

![Figure 5](image)

Figure 5: Comparison between the residual contaminations after the cleaning in place process (a) with a pulsed flow (b) with a steady state flow.
CONCLUSION

The study of the cleanability of the entry bowl of a Scraped Surface Heat Exchanger (SSHE) emphasized the effects of pulsed flows in the slip weakening and bacterial biofilm adhering to the wall geometry. The electrochemical measurements have shown the beneficial effect of pulsations on the mean value of wall shear stress for closed surfaces where the flow is confined between the walls of the geometry. For open surfaces, the effect of pulsations is less evident. The use of cycles with heterogeneous combinations of amplitudes and frequency pulsations could induce an increase in shear forces and subsequently improve the cleanability.

REFERENCES