SOFTWARE-GUIDED CLAMP-ON POWER ULTRASOUND SOLUTION FOR FOULING MITIGATION IN TUBULAR HEAT EXCHANGERS

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ABSTRACT

A new clamp-on power ultrasound solution is being developed for tubular heat exchangers (HX). This system features software-controlled ability to guide the cleaning effect, to reach also the most challenging locations. The new solution was evaluated by finite-element simulations, and field tests are being carried out on tubular HX. Preliminary results show that the new solution is capable of fouling prevention. The results suggest good potential also for fouling cleaning. In conclusion, the new software-guided clamp-on power ultrasound solution was proven valuable since it permits on-site fouling mitigation, without process interruptions, and by increasing the physical cleaning cycle of tubular HX. The solution will thus result in significant savings in equipment and maintenance costs as well as decreasing energy and production losses.

INTRODUCTION

Scaling and fouling build up are known problems that occur across all industries and cause major technical challenges as well as economical losses. Regardless of the equipment type and geometry, scaling and fouling occur on the inner surfaces of the equipment and over time result in decrease of production efficiency either through heat transfer degradation or flow and pressure drops. In fact, various studies have shown that fouling/scaling in heat exchangers (HX) result in roughly 0.25% of the gross domestic product (GDP) losses for industrialized countries and contribute to the 1-2.5% of global CO2 emissions. To address these inefficiencies and high fouling/scaling mitigation costs, various chemical or physical methods are used to mitigate or remove scaling/fouling [1]-[4].

In most industries, the go-to method for cleaning of an HX is hydroblasting, which is inefficient since it does not address the performance losses before the equipment is taken offline for cleaning. Production stoppages, decreased operation time, and decreased life cycle of equipment also cause significant disruption and costs to operations. Additionally, hydroblasting can damage delicate parts of a production line as it relies on high-pressure water jetting. It can also cause health risks to the operators and result in unnecessary high level of water consumption. In contrast to offline cleaning, some methods of online scale prevention and fouling mitigation are ion exchange, addition of chemicals and scale inhibitors. These too are inefficient and anti-scaling agents may not only change the solution chemistry, but in some cases, they can also be harmful to the environment as well as cause health problems for human and aquatic life [5], [6].

As an alternative to traditional cleaning and mitigation methods in the industry, in the recent decades ultrasonic cleaning has been a keen topic of interest. Previously ultrasonic cleaning has only been limited to the automotive industry and laboratories where small equipment parts were immersed in baths fitted with ultrasonic transducers. The equipment then and now the HX are immersed in liquid filled baths subjected to ultrasonic vibration, where the acoustic pressure from the ultrasonic waves creates microcavities in the liquid known as cavitation. The rapid growth and implosion of the cavitation bubbles result in microjetting directed onto the surface that needs to be cleaned. The impact results in disruption of the surface and removes any residues attached to the metal surface. In most cases, the liquid solution in the bath is specifically tailored to the equipment and fouling type, and thus speeds up the cleaning process further. The presence of the acoustic waves throughout the liquid solution enables the user to clean even the hard-to-reach points and removes the need for surface sweeping, hence significantly decreasing the cleaning time as well as increasing cleaning quality and operating performance. The small but evenly distributed acoustic pressure field mitigates any risk of damage to the delicate parts of the equipment, eliminates the need for overconsumption of water and does not expose the personnel to any health risks related to hydroblasting [7], [8].

The main limiting aspect of ultrasonic baths are their size and the necessity to perform the cleaning offline. Any equipment that requires cleaning should be removed from the production line and completely immersed in the bath. Additionally, the other limiting factor is the chemistry of the cleaning liquid, that may cause challenges with some HX materials. To overcome these challenges, service providers have tried to develop online and externally applicable solutions such as Altum Technologies' Zero-Process-Downtime (ZPD) ultrasound solution.

ZPD is a clamp-on power ultrasound solution that completely removes the need for production stops, changes to the process or equipment and manual offline cleaning. The clamp-on power ultrasound solution is installed and operated while the production is running and can be used for both fouling/scaling prevention as well as cleaning. It does not only increase the process up-time, but also keeps the efficiency of the HX at its highest capacity while cleaning the equipment in real time. Furthermore, the clamp-on power ultrasound solution almost completely removes health and safety hazards by keeping the HX clean, thus minimizing the need to use chemicals or open the equipment for manual cleaning. Consequently, resulting in reduction of energy consumption and lowering of CO_2 emissions. The main difference between ZPD ultrasound system and its competitors is that it combines traditional ultrasound cleaning with proprietary beam steering software to focus the ultrasonic cleaner field as necessary [9], [10]. Additionally, the ZPD ultrasound system takes high power ultrasound and seamlessly integrates it to different production equipment on-line in real time through optimization and remote monitoring via internet (IoT).

The objectives of this study are to evaluate, by computer simulations, ultrasonic beam steering in 3D CAD models of tubular heat exchangers, and to test by experimental trial the suitability of the ZPD solution for fouling mitigation in a real tubular HX.

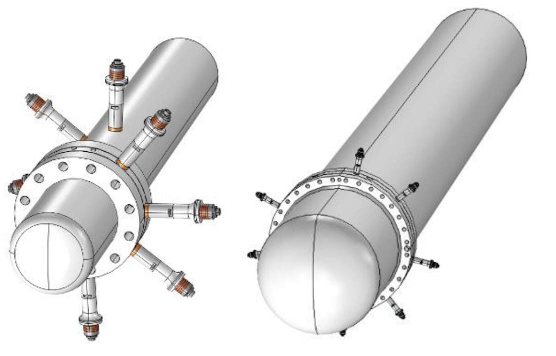

Fig. 1. Simulation geometries: a small-scale U tube HX and a large-scale U tube HX, each sonicated by eight power ultrasound transducers.

METHODS

Finite-element simulations

Ultrasonic cleaner fields were studied by finite-element modelling (FEM) in two different tubular heat exchanger (HX) models, including a small-scale U-tube HX (1.8 m long x 0.34 m diameter) and a large-scale U-tube HX (7.8 m long x 1.1 m diameter) (Fig. 1). The geometries were extracted from the 3D CAD models based on the blueprints of these heat exchangers. The small-scale HX included fluid in the pipes and on the shell side, whereas the large HX included fluid inside the pipes and gas on the shell side.

FEM simulations were carried out in the frequency domain by COMSOL Multiphysics (version 5.6) software, using the solid mechanics and pressure acoustics modules. Linear elasticity was assumed.

Eight piezoelectric power ultrasound transducers, operating at a 20 kHz frequency, were used. In the small-scale HX four transducers were attached at the external surface of the tubesheet, and the remaining four were attached to the shell. In the large-scale HX all the eight transducers were attached to the tubesheet.

The simulated transducers were attached in ideal contacts with the HX surfaces, whereas real transducers are attached using a dry-contact and a specific clamp-on mechanism. Figure 2 shows a 3D CAD representation of the real attachment.

The ultrasonic driving waveforms were altered by Altum's beam steering software control, using the first iteration of the patented methodology. Six different driving software settings were tested.

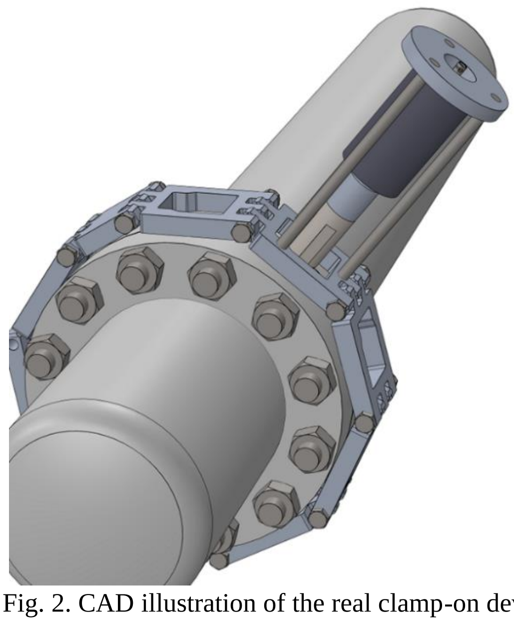

Fig. 2. CAD illustration of the real clamp-on device and the attached ultrasonic transducer with an enclosure.

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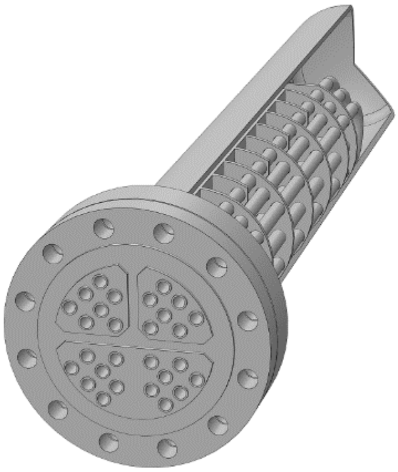

Fig. 3. Internal structure of the small-scale HX model.

Figure 3 shows internal structure of the small-scale HX. The ultrasonic displacement field (u_{tot}), that was delivered, was evaluated in the tubesheet and the tubes. At the internal surfaces of the tubes, normal displacement field (u_n) was evaluated. Moreover, acoustic pressure field (p) was evaluated at the internal boundary of the tubes.

Experimental trial

Feasibility of the proposed methodology was evaluated by preliminary experiments in the small-scale HX, in a laboratory setup. The laboratory environment and instrumentation allowed monitoring of multiple parameters of the HX. The key parameters indicating occurrence of fouling in this trial were temperature differences between the inlet and outlet, on both the shell and tube sides, as these are directly linked to the heat exchange efficiency. Fouling was induced on the shell side by spiking the water flow with calcium chloride salt and soda ash (sodium carbonate).

Fouling prevention was evaluated for a duration of 12 days. The sonication program was selected based on the simulated predictions.

RESULTS

Simulations in small-scale HX

Figure 4 illustrates the ultrasonic displacement field generated in the tubesheet of the small-scale HX by six different sonication program settings. It is shown that the software control permits steering of the loci of focal maxima, as well as altering the strengths of the focal maxima.

Figure 5 shows a top view of the displacement field in the small-scale HX. Importantly, the displacement field is delivered from the tubesheet to the HX tubes and propagates throughout the geometry, including the U-section. The displacement fields in the tubes feature standing waves between the open ends of each tube.

Sonication program setting affected the average strength of the displacement field delivered, and setting #2 provided in this case the strongest displacement field. Results in Figures 4© an©(c) are consistent in this regard.

Average (root-mean square) sonication fields, as detected across the internal surfaces of the tubes, are summarized in Table 1. In addition to the displacement field, an acoustic pressure field inside the tubes is evaluated.

Table 1. Normal displacement and acoustic pressure by different sonication programs in the small-scale HX, characterized by a root-mean square and standard deviation across the internal surfaces of the tubes

Sonication program	u_n (μm)	p (kPa)
0	3.20 ± 1.71	703 ± 370
1	3.89 ± 2.00	1365 ± 655
2	5.43 ± 2.75	1552 ± 792
3	4.08 ± 2.12	1104 ± 522
4	4.91 ± 2.43	1433 ± 780
5	5.11 ± 2.60	1696 ± 820

Simulations in large-scale HX

Figure 6 illustrates the ultrasonic displacement field generated in the tubesheet of the large-scale HX by six different sonication program settings. Also in this case, it is clearly shown that the software control permits steering of the loci of focal maxima.

Figure 7 shows a side view of the displacement field in the large-scale HX. To improve visualization, only one tube is shown, and it is shown at its end segments (i.e. the intermediate range has been withdrawn). Importantly, the displacement field is delivered from the tubesheet to the heat exchanger tube and propagates throughout the geometry, including the U-section. The displacement fields in the tube feature standing waves between the open ends of each tube.

Average (root-mean square) sonication fields, as detected across the internal surfaces of the tubes, are summarized in Table 2.

Table 2. Normal displacement and acoustic pressure by different sonication programs in the large-scale HX, characterized by a root-mean square and standard deviation across the internal surfaces of the tubes

Sonication program	u_n (μm)	p (kPa)
0	0.49 ± 0.27	141 ± 77
1	0.62 ± 0.35	166 ± 93
2	0.57 ± 0.31	137 ± 73
3	0.63 ± 0.35	152 ± 73
4	0.63 ± 0.34	146 ± 78
5	0.58 ± 0.33	140 ± 77

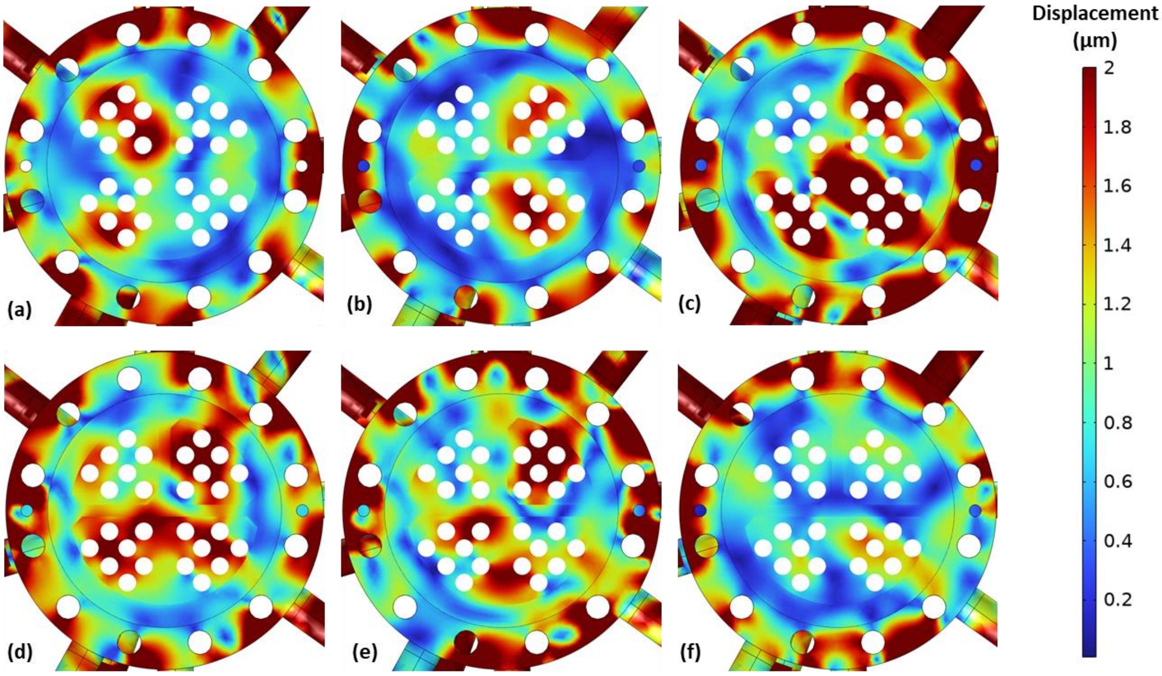

Fig. 4. Ultrasonic displacement field generated in the tubesheet of the small-scale HX

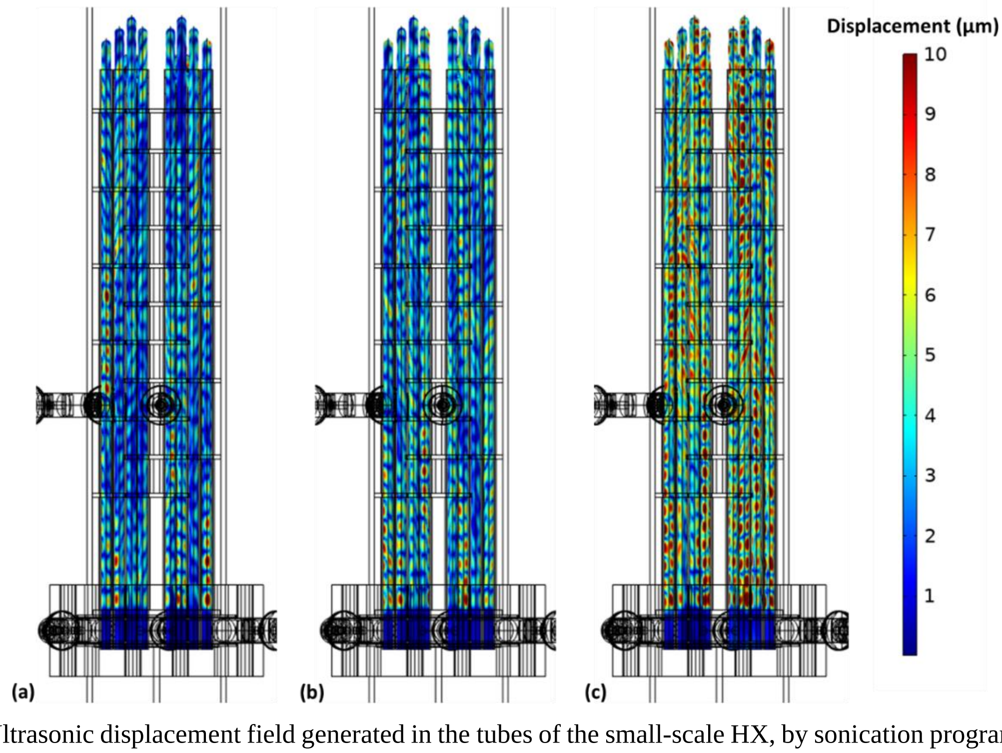

Fig. 5. Ultrasonic displacement field generated in the tubes of the small-scale HX, by sonication program settings (a) 0, (b) 1 and (c) 2.

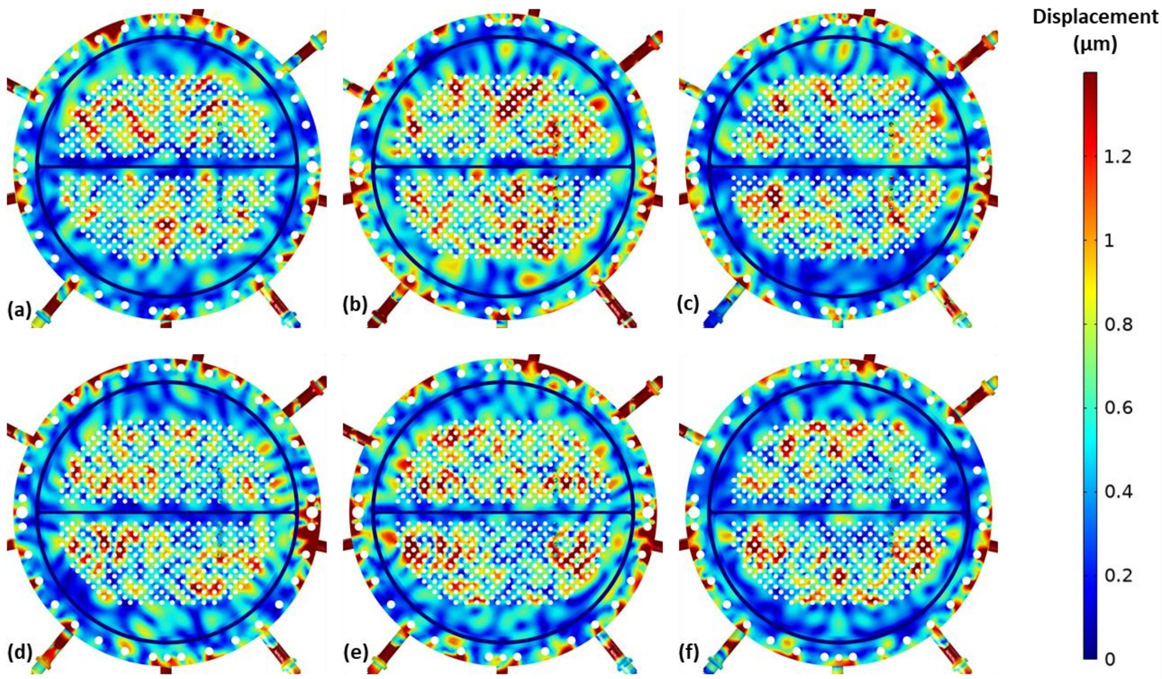

Fig. 6. Ultrasonic displacement field generated in the tubesheet of the large-scale HX

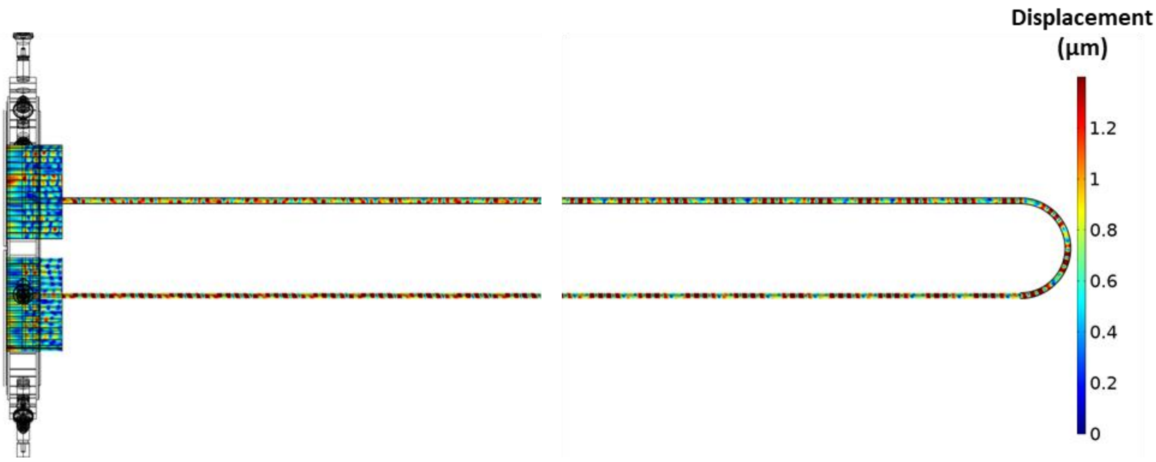

Fig. 7. Ultrasonic displacement field generated in the tubes of the large-scale HX. One of the U tubes is visualized at its entire length, the middle-section of it been excluded to improve the visualization. The field is generated by sonication program setting 1.

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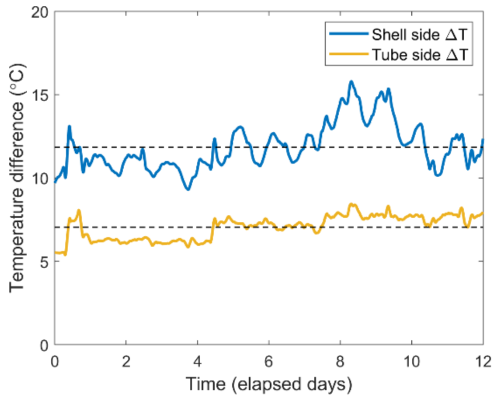

Fig. 8. Temperature differences (ΔT) measured at the shell side (blue) and tube side (yellow) during the fouling prevention run. Both remain nearly constant throughout the trial. Dashed lines represent the related ΔT averages.

Experimental trial in small-scale HX

Figure 8 shows temperature differences (ΔT) during the fouling prevention run. Both the shell side and tube side temperature differences (ΔT) stayed nearly constant, indicating minimal disturbance to the heat exchange efficiency and hence no fouling buildup. Had there been fouling buildup, one would expect ΔT to approach zero as there would not be any heat exchange between the two sides.

Figure 9 (right) shows borescope photographs taken after the prevention run, confirming that the HX surfaces remained essentially clean. In comparison Figure 9 (left) shows reference photographs taken after similar run, without fouling prevention by sonication. The reference photographs indicate that normally the HX surfaces become covered by a large fouling buildup under the same conditions.

DISCUSSION

It was predicted by simulations that the clamp-on power ultrasound solution permits ultrasonic fouling mitigation in tubular HX. A preliminary experimental trial showed good capability for fouling prevention.

The software control permitted steering of the cleaner field maxima. The result of steering was clear, in particular, at the transverse cross-section of the tubesheet. On the other hand, it was predicted that the cleaner field is coupled between the tubesheet and tubes, and is propagated long distances along the tubes by carrying the cleaner effect. Importantly, the ultrasonic field covered not only the tubes of the small-scale HX but also those of the large-scale HX.

The physical mechanism which explains wave propagation in solid tubes is guided waves. Reflections at the free ends of the tube resulted in standing tube waves which magnify the delivered cleaner field.

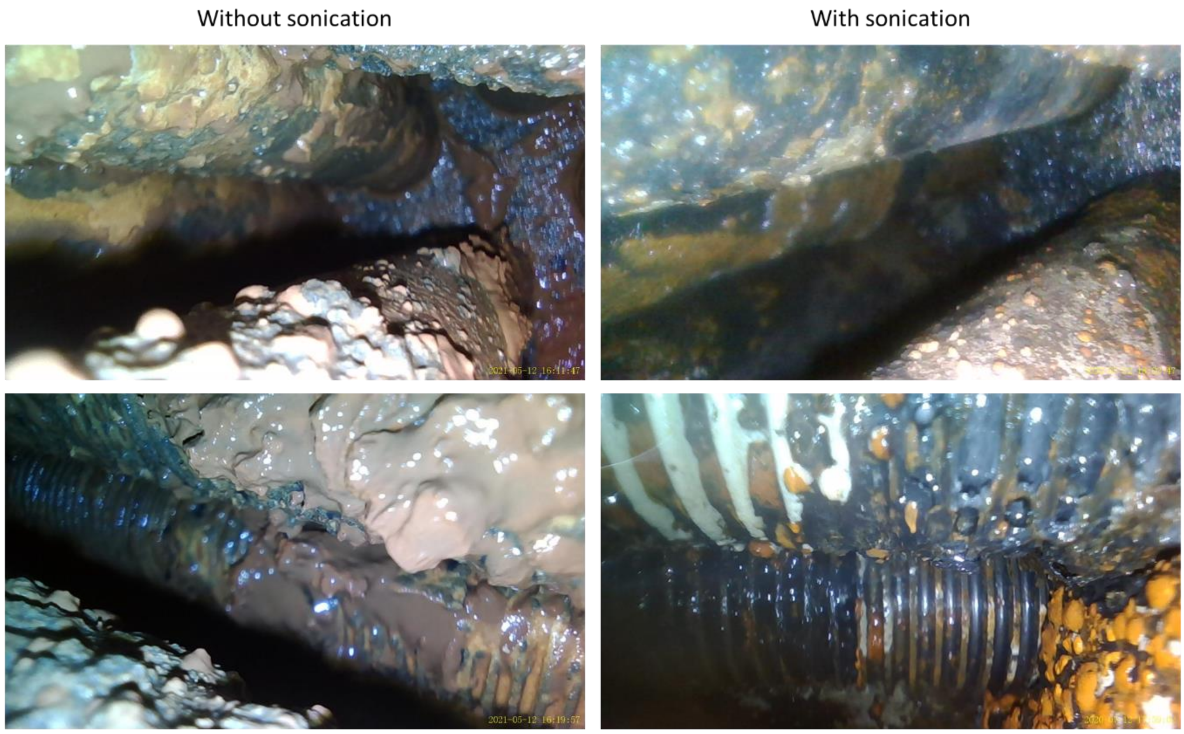

Fig. 9. Borescope images taken after 12 days of HX operation with fouling chemicals. Without sonication (left) and with sonication (right).

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Ultrasonic coupling between the tubesheet and tubes seems more complicated than what one would intuitively think. For instance, from Fig. 4(a) one would expect a field weighted on the left side of the tubes, and from Fig. 4(b) a field weighted on the right side of the tubes. Observation respectively of the tubes from the top side, Figs. 5(a) and 5(b), suggests that the effect is not that obvious. Closer observation of the field within the tubesheet reveals details of the field coupling, being currently investigated by us.

Nevertheless, these preliminary simulation results predicted that the software beamforming and steering of the ZPD solution can affect the cleaner field delivery in real tubular HX geometries. This is an important step while developing the new technology.

It is essential to note, that the software beamforming and steering permits altering the cleaner field at specific intervals during the sonication. This results in the intensity maxima and therefore the cleaning effect changing locations. Thus, an even cleaning or fouling prevention effect is achieved throughout the structure.

While good fouling prevention was observed in a small-scale HX, a question arise whether the solution is scalable to larger HX units. The simulations predicted that the solution is well scalable also to larger HX geometries.

Another question that arise is, whether the solution is capable of cleaning tubular HX. We are also evaluating the cleaning ability in the small-scale unit, and the preliminary results have been promising. Clearly, however, ultrasonic cleaning is more challenging than fouling prevention, since a stronger cleaner field is needed to detach the fouling.

The clamp-on power ultrasound solution does not introduce any changes to the production process. Therefore, during fouling prevention a build up in a location, where previously has been none, is not possible. However, in instances of cleaning the fouling removed can be carried downstream with the flow.

It is important to note that while the experiments described in this paper were carried out with calcium-carbonate based fouling, the proposed approach is applicable to other types of fouling as well. Nevertheless, further research is needed to examine the related sonication parameters.

CONCLUSION

This study suggests that the clamp-on power ultrasound solution is a valuable alternative to traditional cleaning methods. The software-guided clamp-on power ultrasound solution permits on-site fouling mitigation, without process interruptions. By increasing the physical cleaning cycle of heat exchangers, the software-guided solution will thus result in significant savings in equipment and maintenance costs as well as decreasing energy and production losses.

The results indicate that the software-guided clamp-on power ultrasound solution is suitable for fouling prevention in particular, and preliminary experiments show promising results in fouling removal too. A traditional cleaning cycles-based approach has a predictable maintenance cost, but usually causes production loss and higher energy consumption towards the end of the cycle. Fouling prevention with software-guided clamp-on power ultrasound has a cost comparable to the maintenance cost of the traditional approach, but offers longer cycle length, lower energy consumption and lower production loss due to fouling. Therefore, compared to the traditional approach, the software-guided clamp-on power ultrasound solution offers greater economic, environmental, and financial benefits for the industry.

NOMENCLATURE

u_{tot} Total displacement, m
u_n Normal displacement, m
p Acoustic pressure, Pa
ΔT Temperature difference, ˚C

REFERENCES

[1] Garrett-Price, B. A., Smith, S. A., Watts R. L., and Knudsen, J.G., *Industrial fouling: problem characteri-zation, economic assessment, and review of prevention, mitigation, and accommodation techniques*, Pacific Northwest Laboratory, United States Department of Energy, United States, 1984. DOI: 10.2172/ 5310685.

[2] Lestina, T., *Heat Exchangers Fouling, Cleaning and Maintenance*, in Handbook of Thermal Science and Engineering, F. A. Kulacki, ed. Cham, pp. 1-33, Springer International Publishing, 2017. DOI: 10.1007/ 978-3-319-32003-8_24-1.

[3] Steinhagen, R., Müller-Steinhagen, H., and Maani, K., *Problems and Costs due to Heat Exchanger Fouling in New Zealand Industries*, Heat Transfer Engineering 14(1):19-30, 1993. DOI: 10.1080/01457639308939791.

[4] Müller-Steinhagen, H., Malayeri, M. R., and Watkinson, A. P., *Heat Exchanger Fouling: Environmental Impacts*, Heat Transfer Engineering 30(10-11):773-776, 2009. DOI: 10.1080/01457630902744119.

[5] Jafari M. et al., *A comparison between chemical cleaning efficiency in lab-scale and full-scale reverse osmosis membranes: Role of extracellular polymeric substances (EPS)*, Journal of Membrane Science 609:118189, 2020. DOI: 10.1016/J.MEMSCI.2020.118189.

[6] Naddeo, V., Borea, L., and Belgiorno, V., *Sonochemical control of fouling formation in membrane ultrafiltration of wastewater: Effect of ultrasonic frequency*, Journal of Water Process Engineering 8:e92–e97, 2015. DOI: 10.1016/j.jwpe.2014.12.005.

[7] Kieser, B., Goode, A., and Philion, R., *From Practice-to-Theory-to-Practice: Advances in the Cleaning of Heat Exchangers Using Ultrasound*, Proc International Conference on Heat Exchanger Fouling and Cleaning, 2013.

[8] Schulz, C. H., and Kieser, B., *Understanding the Value of Cleaning - Gains from the Use of Ultrasonic Cleaning of Large Industrial Equipment*, Proc International Conference on Heat Exchanger Fouling and Cleaning, 2019.

[9] Mustonen, J. A., Tommiska, O. M., Holmström, A., Rauhala, T., Moilanen, P., Gritsevich, M., Salmi, A., and Hæggström, E., *FEM-based Time-Reversal Enhanced Ultrasonic Cleaning*, Ultrasonics Sonochemistry 79:105798, 2021.

[10] Tommiska, O., Moilanen, P., Mustonen, J., Rauhala, T., Gritsevich, M., Salmi, A., and Haggstrom, E., *Simulation of Forward Propagated Signals in Acoustic Time Reversal*, Proc IEEE International Ultrasonics Symposium, 2515–2518, 2019. DOI: 10.1109/ ULTSYM.2019.8926189.