Clean-in-Place Monitoring of Different Food Fouling Materials using Ultrasonic Measurements

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Abstract:

Clean-in-Place is an autonomous technique used to clean the internal surfaces of processing equipment in the food and drink sector. However, these systems clean for a longer time than required with negative economic and environmental impacts. In this work, an ultrasonic sensor system was developed to monitor the cleaning of different food fouling materials at laboratory scale. The fouling removal of three different food materials was also studied at different cleaning fluid temperatures. The three food materials had different cleaning mechanisms, which could be monitored successfully with the ultrasonic system. Tomato paste and gravy appeared to be cleaned by mechanical forces whereas malt extract dissolved into the cleaning water. The results yielded from the cleaning of the malt was found to be repeatable whereas the tomato and gravy were more variable between repeat experiments. It was found that changes in recorded ultrasonic signals were mainly affected by the area of fouling that covered the transducer's active element.

Keywords: Ultrasonic Measurements, Clean-in-Place, Process Analytical Technologies, Food Materials

1. Introduction:

Cleaning of processing equipment is an essential operation in sectors such as food and drink, pharmaceutical and Fast Moving Consumer Goods (FMCG). Cleaning is performed to ensure processing equipment remains hygienic and to remove any internal surface fouling which may have accumulated during processing. Any remaining fouling can have negative effects on the performance of processing equipment (e.g. heat transfer rates in heat exchangers) and can cause cross contamination issues if it becomes dislodged during subsequent processing. This is of critical importance when processing equipment is used to produces numerous different products, some containing allergens, as is often the case in the food and drink sector. Most processing facilities clean their equipment using a method called Clean-in-Place (CIP). This is an autonomous process which utilises water and chemicals to perform the cleaning and does not require equipment disassembly or manual intervention by factory workers. CIP processes clean the equipment by a combination of: time, chemicals, temperature and mechanical force. Different cleaning chemicals and CIP processes are utilised depending on the physical chemical properties and volume of the fouling material. Most CIP processes are designed specifically for the equipment they are cleaning but generally feature five stages: 1) pre rinse 2) chemical cleaning 3) post rinse 4) sanitisation 5) final rinse (Fryer, Christian, & Liu, 2006). CIP processes are routinely validated to ensure the equipment is clean and free of microorganisms after a cleaning cycle. This validation is performed using Adenosine Triphosphate (ATP) kits or growth and microbial enumeration tests (Fratamico, Annous, & Guenther, 2009).

Within the food and drink manufacturing sector most processing equipment is used to manufacture numerous different products each with a unique formulation and fouling behaviour. In general, CIP systems are designed for the worst case fouling product and over-cleaning is a common occurrence. This over-cleaning has significant negative economic and environmental impacts resulting from the unnecessary overuse of resources such as water and energy and lost production time. It has been reported that cleaning is responsible for 30% of the energy used in dairy processing (Eide, Homleid, & Mattsson, 2003), and approximately 35% of the water use in beer production (Pettigrew, Blomenhofer, Hubert, Groß, & Delgado, 2015). This problem is increased in the current climate where consumer preferences are driving mass customisation of products (Vries et al., 2018). This mass customisation leads manufacturers to produce more batches (each of lower volume) requiring a cleaning operation between every batch. Therefore, the total time spent cleaning equipment rather than in production, is increasing.

Research performed to optimize CIP processes has generally focused on understanding the effects of different cleaning parameters (e.g. water flow rate) (Fan, Phinney, & Heldman, 2018), or studying fouling and cleaning using a range of different measurements (Fratamico et al., 2009). The most common measurement techniques include simple sensors monitoring either temperature (Vieira, Melo, & Pinheiro, 1993) or pressure (Riverol & Napolitano, 2005) at different locations in the equipment or methods that detect the presence of fouling or chemicals in the cleaning water (Lyndgaard, Rasmussen, Engelsen, Thaysen, & Van Den Berg, 2014) (Berg, Ottosen, Berg, & Ipsen, 2017) (Van Asselt, Van Houwelingen, & Te Giffel, 2002). However, in many cases the fouling material will remain adhered to the internal walls of the processing equipment and measurements of the cleaning water would be unsuitable to determine the actual cleanliness of the equipment. To monitor the degree of surface fouling numerous different techniques have been investigated. In a 2012 review of fouling detection methods (E. Wallhäußer, Hussein, & Becker, 2012a), in heat exchangers, it was stated that the main sensor techniques were based on either electrical (e.g. (X. D. Chen, Li, Lin, & Necati, 2003) (Guérin, Ronse, Bouvier, Debreyne, & Delaplace, 2007) (Tlili, Rousseau, Ben Amor, & Gabrielli, 2008)) or acoustic methods (e.g. (Pereira, Mendes, & Melo, 2009) (P. M. Withers, 1996) (Úbeda, Hussein, Hussein, Hinrichs, & Becker, 2016)). Optical sensors utilising ultraviolet fluorescent techniques have also been used to monitor cleaning processes (P. M. Withers, 1996) (Simeone, Deng, Watson, & Woolley, 2018) (Simeone et al, 2016) and a fibre optical device has been used to monitor biofilm fouling in a brewery water pipe (Tamachkiarow & Flemming, 2003). However, optical imaging technologies require lighting to enable imaging of the surface under investigation so they would not be suitable in pipes or processing equipment where suitable illumination would be extremely challenging (e.g. heat exchangers).

Various researchers have investigated acoustic techniques to measure fouling and cleaning in systems representative of processing equipment. These techniques can generally be split into three methods: 1) guided waves, 2) low frequency vibrations (<20 KHz), 3) Ultrasonic (US) techniques. Guided wave techniques utilise shear (transverse) waves, which propagate along the surface between a solid and fluid, or through a solid material located between two fluids. For inspection and measurements in pipes, guided wave techniques generally use separate transducers for wave generation and detection and can propagate waves either along a length section of a pipe or around its circumference. Guided wave techniques have been used to measure a range of different fouling materials in pipes (Hay & Rose, 2003), (Lohr & Rose, 2003), (Jaidilson Jó da Silva, Lima, & da Rocha Neto, 2007), (J J Silva, Silva, Lima, & Neto, 2008). The group of Rose demonstrated that guided wave techniques were capable of detecting the presence of internal surface fouling of materials such as grease, oils and fats in pipes filled with water (Hay & Rose, 2003) (Lohr & Rose, 2003). The group of Silva performed experiments in flow conditions and demonstrated the capabilities of guided wave techniques for monitoring fouling growth in pipes using a variety of different signal processing methods (Jaidilson Jó da Silva et al., 2007) (J J Silva et al., 2008). Vibration techniques feature two different components. The first is some type of mechanical or electro-mechanical instrument, which causes a vibration in the system under inspection. The second component is a sensor to detect these vibrations (e.g. piezoelectric transducer). The principle behind fouling detection using vibration methods is that any fouling on the internal surface of the pipe or test section will have an effect on vibrations within the material, which can be detected by the sensor. Pereira et al. used a mechatronic sensor to monitor dairy fouling, and found that the amplitude of the detected vibrations reduced as the thickness of the fouling layer increased (Pereira, Rosmaninho, Mendes, & Melo, 2006). The same group used a similar technique to study the cleaning of shampoo residue and also studied the effects that temperature and flow rate had on the fouling layer removal (Pereira et al., 2009). Merheb et al., 2007 studied dairy fouling in a heat exchanger and found that the recorded acoustic power reduced as the amount of surface fouling increased (Merheb, Nassar, Nongaillard, Delaplace, & Leuliet, 2007). Acoustic hammer and microphone techniques have shown that the frequency content and decay in received acoustic signals both reduced when the pipe test sections were fouled with a paraffin resin (Jaidilson Jó da Silva, Lima, Neff, & da Rocha Neto, 2009) (Jó, Marcus, Lima, Neff, & Sérgio, 2009) .

Ultrasonic techniques feature one or more transducers operating in the US frequency range (> 20 KHz), and were one of the first techniques proposed to monitor fouling in processing equipment. Withers used two US transducers operating in a transmission mode system to measure the thickness of a range of food and non-food fouling materials (P. Withers, 1994) (P. M. Withers, 1996). This work was performed with the fouling material applied to the internal surface of a pipe section, which was then flooded with water and showed that US velocity can be used to measure fouling layer thicknesses between 0.5 – 6 mm. Other researchers used a single US transducer operating in reflection mode and an Artificial Neural Network (ANN) to monitor the thickness of dairy fouling (Wallhaußer, Hussein, Hussein, Hinrichs, & Becker, 2011). Their measurements were performed in a bespoke experimental container with the fouling material located on one internal surface before being filled with water. They recorded US waves reflected initially from the wall/fouling layer interface and those which travelled through the water before been reflected back. These reflected signals were analysed in terms of their acoustic impedance, acoustic energy, and logarithmic decay. These features were then used as inputs for an ANN, which was capable of detecting the presence of fouling with an accuracy around 99%. This group continued this work on dairy fouling in a static system and performed a sensitivity analysis that showed that the recorded US results were more dependent on the acoustic impedance of the fouling material than the fouling layer thickness (E. Wallhäußer, Hussein, & Becker, 2012b). They also performed work where they created fouling layers of either protein or mineral materials (E. Wallhäußer, Hussein, Hussein, Hinrichs, & Becker, 2013) and investigated different classification methods for determining the presence of fouling. They showed that Support Vector Machines (SVM) performed better in classification than ANN, with higher accuracy when predicting the presence of protein than mineral fouling. This group also recorded US measurements during the dynamic cleaning of dairy material. They showed that with different features extracted from the recorded US signals, classification methods could be developed with accuracies of 98% in predicting the presence of dairy fouling (Eva Wallhäußer et al., 2014) (Úbeda et al., 2016). Chen et al., developed a method which utilised an US transducer in contact with the external wall of a rectangular duct section (B. Chen et al., 2019). On the internal surface of this duct, adjacent to the transducer, a 6mm thick layer of wax was placed. This wax was representative of a layer of fouling material. They flowed water through the duct for a period of approximately three hours and showed that coda wave interferometry techniques, applied to the recorded US signals, could successfully be used to monitor the removal of this wax layer. Although there has been progress in the development of US techniques to detect the presence of fouling the majority of this work has focussed on either dairy fouling or model materials.

In this work, an US system, that is capable of monitoring the cleaning of different fouling materials relevant to the food and drink manufacturing sector is described. A range of cleaning fluid temperatures and different signal and data processing methods were investigated. Images were recorded during cleaning and used to determine which aspects of the fouling layers had the largest effect on the recorded US signals.

2. Material and Methods:

2.1 Ultrasonic methods

Ultrasonic techniques operate by transmitting low amplitude, high frequency acoustic waves through the system under investigation. They are an attractive sensing technology due to their small size, low cost and ability to perform measurements non-invasively on opaque systems (Watson, 2015). This work utilised a single US transducer used for both transmitting and receiving the US signal. This type of system is called a reflection mode system and have been used for a variety of industrial applications including corrosion monitoring (Cheong, Kim, & Kim, 2017) and flow monitoring (Al-Aufi et al., 2019).

The US system developed during this work features an US transducer attached to the bottom of a test section (Figure 1). The US wave was transmitted from the transducer through the solid pipe wall. At the wall/fouling layer interface a proportion of the wave was reflected. The wave then propagated back through the wall before being detected by the same transducer. The proportion of the wave that was not reflected from the wall/fouling layer interface propagated through the fouling layer until it reached the fouling layer/water interface where another proportion was reflected, and the remainder transmitted into the water. Figure 1 depicts the fouling layer/water interface as a solid line but in reality this would be much more complex due to constantly changing geometry and localised material properties, resulting from the flowing water.

When an US wave becomes incident at an interface, the ratio of the reflected pressure amplitude to the incident pressure amplitude can be determine by the reflection coefficient (R):

$$R = (Z_2 - Z_1)/(Z_2 + Z_1) \quad (1)$$

Where Z is the acoustic impedance define by:

$$Z = \rho v \quad (2)$$

Where ρ is the density of the material and v is is the velocity of a longitudinal US wave in the material. The above equation indicates that reflection increases with the size of the impedance mismatch. However, strictly, R is a function of incident angle θ and can change markedly with θ. The reflection coefficient and impedance of the materials (e.g. fouling layer) can be calculated by measuring the magnitude of the reflected US waves. Previous research has shown that acoustic impedance calculations of material adjacent to a test section wall can be used to determine the presence of fouling ((Eva Wallhäußer, Hussein, Hussein, Hinrichs, & Becker, 2011) (E. Wallhäußer et al., 2013)). However, these methods generally require the reflected wave to be separated in time from the transmitted wave and this is only true when the wall thickness ($\delta_{w,min}$) is greater than the value specified by:

$$\delta_{w,min} \geq Nv/2f \quad (3)$$

Where N is the number of wave cycles in the ultrasonic pulse, v is the speed of US wave in the wall material and f is the frequency of US wave. If the wall thickness is greater than this value, the reflected waves are superimposed upon one another and signal and data analysis becomes challenging. Some proportion of the US waves may be reflected from the fouling layer/water interface. However, this proportion is likely to be extremely small due to the changing geometry and properties described above, and the similar values of acoustic impedance for the water and fouling material. Chen et al., 2018 were able to monitor the removal of a fouling layer when reflected US signals were overlapped using a coda wave interferometry technique (B. Chen et al., 2019). During the formation and subsequent cleaning of a fouling material the adhesion between the fouling layer and the surface will change. It has been shown that US techniques can be used to determine the degree of adhesion between a surface and a whey protein fouling layer (Collier et al., 2015). Ultrasonic wave propagation is highly dependent on the temperature of the system in which it propagates (Al-Aufi et al., 2019). To eliminate or minimise any temperature effects when utilising US techniques the temperature should be kept constant during measurements, or recorded and accounted for during subsequent data analysis.

2.2 Experimental rig and materials

An experimental laboratory rig was built to reproduce the cleaning process of a pipe inner wall (Figure 2). It was a square, closed channel rig constructed from Perspex with a Stainless Steel (SS) 430 bottom wall. Stainless steel was selected for the fouling wall to represent industrially relevant materials. The remainder of the rig was constructed from Perspex to enable visual access to the progression of the cleaning. Although the majority of industrial piping is cylindrical, a flat section was used for these experiments to aid the imaging of the cleaning process. One side of the rig was connected to a tap and the other side to a drain. The main dimensions (in millimetres) and the parts of the rig are shown in Figure 2.

Three different food materials were used to generate the fouling. These were tomato paste, gravy and concentrated malt extract. The tomato paste was Napolina Double Concentrate Tomato Pure and the ingredients were: tomatoes, acidity regulator (citric acid), density: 0.84 kg/m^3. The Gravy was Bisto Favourite Gravy Granules with the following ingredients: potato starch, maltodextrin, palm oil, salt, wheat flour, colour (E150c), sugar, flavour enhancer (E621, E635), emulsifier (E322), density once dissolved in water: 0.95 kg/m^3. The concentrate malt was taken from a Coopers Real Ale beer kit with the following ingredients: malted barley, hops, yeast and water, density: 1.12 kg/m^3. The gravy was prepared by mixing 10 grams of granules and 10 ml of tap water in a beaker at 70℃ for 1 minute with continuous stirring. The other materials did not require preparation. The fouling film was created by depositing 15 grams of one of the food materials on to the centre of the bottom plate of the rig. It was then spread evenly with a spatula to form a uniform layer of approximately 5 mm thickness. It was left to dry (and in the case of the gravy, also cool down) for ten minutes before beginning any cleaning experiments.

2.3 Experimental method

Once the fouling film was prepared, the rig was flooded slowly with water at the desired temperature. This was performed to ensure the rig was the same temperature as the cleaning water to reduce the effects of temperature variation on the US measurements during the acquisition of the data. After one minute, the inlet tap was opened and water flowed through the experimental rig. The flowing water was allowed to remove the fouling layer and the experiment finished when all of the fouling was removed. The water flow rate was calculated by measuring the volume of water exiting the experimental rig during a known time period. Nearly all CIP systems utilise a chemical cleaning stage. As the fouling materials used in this work were not burnt onto the pipe section, chemicals were not required to remove them. This current work is more representative of the initial pre-rinse stage of a CIP cycle, which generally uses water at ambient temperature without the addition of chemicals.

2.4 Instrumentation

The ultrasonic transducer was a 5 MHz magnetic contact transducer supplied by Olympus. This transducer had a circular active element of diameter 1.27 cm and an area of 1.27 cm^2. A US Box provided by Lecoeur Electronique was used to excite the transducer with an electronic pulse and digitise the received signals. Temperature was recorded by a RTD PT1000 attached to a Pico Technology PT-104 data logger. Images were recorded using two Logitech C270 3MP web cameras. The US Box, PT-104 and web cameras were all attached to a laptop. Bespoke MATLAB software was developed to control the hardware components and acquire the data. The two web cameras were located above and at the side of the US transducer location on the rig to image the cleaning of the fouling materials from two different perspectives (Figure 2).

2.5 Signal and data processing

Figure 3 displays a reflected signal, recorded from the US system. As can be seen the reflected signals are not separated in time from the transmitted signal due to the conditions of Equation 3 not being true. Figure 3 (a and b) shows that there is very little difference in the reflected signal from a clean pipe or one fouled with food materials. However, small changes can be observed when smaller sections of the received waves are studied (Figure 3 c-e). The clean pipe has the largest amplitude of the reflected wave. The gravy and tomato have a slightly reduced amplitude when compared to the clean pipe. The malt fouling has a larger difference than the other two fouling materials. Differences between clean and fouled surfaces can be determined in all of the window locations in Figure 3 (c-e). However, the greatest different is observed in the 4-4.5 µs location where the reflected signal has the largest amplitude in general (Figure 3 c). Signals before 4 µs could not be analysed as these had saturated. It would be possible to reduce the gain applied to the received signal but this would reduce the duration of the received signal due to attenuation, which may make it indistinguishable from noise.

Several different signal and data processing methods were utilised to analyse the received US signals during the cleaning of the fouled material. The first two methods studied the amplitude and energy in a windowed portion of the signal. The third method compared any variation in the signal to a signal from a known clean pipe. The peak-to-peak amplitude (*PPA*) was calculated using the following:

$$PPA = \max_{w_1<t<w_2}(V(t)) - \min_{w_1<t<w_2}(V(t)) \quad (4)$$

Where *V(t)* is the voltage at time *t*, and w_1 and w_2 are the starting and ending times of the processing window. Examples of different signal windows can be seen in Figure 3 (c-e). Relative peak-to-peak amplitude (PPA_r) is the peak to peak amplitude when the wall is dirty (PPA_d) compared to when it is clean (PPA_c). This was used to determine the most suitable signal window location and length.

$$PPA_r = abs(PPA_c - PPA_d)/PPA_c \quad (5)$$

The energy *E* in the windowed signal was calculated using:

$$E = \sum_{t=w_1}^{w_2} V(t)^2 \quad (6)$$

The relative energy (E_r) was used to determine the most suitable window location and length and calculated using:

$$E_r = abs(E_c - E_d)/E_c \quad (7)$$

Where E_c is the energy for a clean pipe and E_d is the energy for a dirty pipe. Root Mean Square Error (RMSE) was used to compare the difference between two waveforms. This was calculated using:

$$RMSE = \sqrt{\frac{1}{(w_2 - w_1)} \sum_{t=w_1}^{w_2} (V_d(t) - V_c(t))^2} \quad (8)$$

Where $V_d(t)$ is the voltage when the wall is dirty at a time t and $V_c(t)$ is the voltage when the wall is clean at the same time t. It was important to determine which portion of the received signals to analyse using the methods proposed above. A section of signal can be analysed by applying a window in the time domain. Example windows can be seen in Figure 3 (c-e). To determine the most suitable location and size of this window analysise were performed using the RMSE (Equation 8) and relative US peak to peak amplitude and energy values described above (Equations 5 and 7), for each of the fouling materials. A received signal was recorded from the clean test section, flooded with water and the fouled test section also flooded with water. Different window locations and sizes were then applied to the received US signals to determine which window locations and sizes gave the greatest difference for the three US analysis methods, when comparing the clean to dirty test section (Figure 4).

The results for the most suitable window location (Figure 4) do not show a clear result and ideal location, with differences identified for the different fouling materials and US data analysis methods. For relative amplitude, a location above 6 µs appears to make no difference for the tomato and gravy but does for the malt. For relative energy a peak in difference is present at 6 µs however after this the results show different trends for the three materials. The results for RMSE generally show a reduction between 5 and 9 µs. As no clear ideal location could be identified from this approach, a location of 6 µs was selected as this appears to be a suitable compromise. The results for the window length show that this has very little effect on the results so a value of 3 µs was selected. The results in Figure 4 also show that the presence of fouling has a slightly larger effect on the US energy than the US amplitude. This is expected as the US energy uses all the points within the windowed signal whereas the US amplitude only uses the maximum and minimum values.

3. Results and Discussion:

The US amplitude, the US energy and the RSME were normalized in between two values, in order to plot them together using a single axis and compare the results between the different fouling materials. The US amplitude (Equation 4) was normalised between 0-5000, the energy (Equation 6) was normalised between 0 – 2.8×10^8 and the RMSE (Equation 8) was normalised between 0-300.

3.1 Tomato paste

The results for the US data recorded during the cleaning of tomato paste are shown in Figure 5. The results show that as the tomato paste was cleaned the US amplitude and the energy increased whilst the RMSE reduced. All three US data features changed at the same locations in time, which was approximately 6:30 – 8:30 minutes. This indicates that all US data features calculated are sensitive to the same aspects of the fouling and there in no benefit in calculating more than one US data feature. The change in the US amplitude during cleaning was the lowest and approximately 55-60%. The change in the US energy was approximately 70-80%, whereas the change in RMSE was approximately 18-2%. The changes in the US amplitude and energy were as expected; as the fouling materials have different physical properties to the flowing water, so would reflect the ultrasonic waves differently (Equations 1 and 2). The results in Figure 5 were consistent with those of Wallhäußer et al., 2013 who found that the US energy in a reflected signal was lower in the presence of dairy fouling when compared to a clean test section. In the first seven minutes of cleaning the coverage area and thickness of the tomato fouling could be seen to reduce in the images but no changes were observed in the US results (Figure 5). It should be noted that during the first seven minutes of the experiment the fouling completely covered the area on the plate opposite to the US transducer's active element area (1.27 cm^2). Therefore, the only change in that region was the fouling layer thickness. This suggests that the US technique utilised within this work is not sensitive to changes in fouling layer thickness in the early stages of cleaning or with fouling not directly above the sensor footprint. This is consistent with the findings of E. Wallhäußer et al., 2012b. The RMSE technique is similar to the decorrelation coefficient method use by B. Chen et al., 2019. However the decorrelation coefficient was used to compare recorded signals from two sensors, one where fouling was present and one without fouling. In addition the decorrelation coefficent only takes into account differences in phase or signal location and not amplitude differences. Both the RMSE method used in this work and the decorrelation coefficient used in Chen et al., 2019 showed comparable results. However, the results in Chen et al., 2019 showed changes throughout the entire cleaning processes. This could be due to the nature of the material they were cleaning (wax), the hardware components utilsied or their signal and data processing methods.

3.2 Gravy

The US results for gravy (Figure 6) showed the same trends as the results for tomato paste (Figure 5). These were an increase in US amplitude and energy and a reduction in RMSE during cleaning. All final values for the three US features were also a similar value as the results for tomato (Energy = 90%, Amplitude = 65%, RMSE = 5%). The RMSE showed a significantly larger change throughout cleaning, which began at a normalised value of 90% before increasing during the first three minutes. Following this, the RMSE reduced quickly between three and five minutes before a more gradual decrease to 11 minutes when the fouling had been removed. The US amplitude and energy both began at lower initial values than the tomato paste (55% and 42% respectively). Once cleaning began these both reduced for three minutes before increasing until the fouling was removed. From the images, it was observed that during these first few minutes the gravy fouling swelled due to absorption of water, which may be responsible for these initial changes in the US results. The initial swelling of the fouling layer has been identified by numerous researchers and was included in the cleaning model for protein fouling proposed by Xin, Chen, & Özkan, 2004. The recorded images suggest cleaning differences between the tomato and the gravy. The tomato appeared to gradually reduce in volume whereas the gravy swelled became partially detached from the test section, with visible movement, before becoming detached at approximately 11 minutes. The gravy results for all US data features show a significant amount of localised variation during the cleaning. These localised variations could be caused by the movement of the swollen gravy or the presence of small bubbles adhering to the surface and the gravy which, were observed. This localised variation is not likely caused by noise as it was not present at the beginning (0-4 minutes) or end of the results (11-15 minutes).

3.3 Malt

The US results for the cleaning of malt (Figure 7) showed the largest variation in the US data features when compared to the tomato paste (Figure 5) and gravy (Figure 6). The results for malt do appear to follow the same general trends as the tomato, which is an increase in US amplitude and energy and a reduction in RMSE. The initial values for US amplitude was 30%, for US energy 20% and RMSE 90%. The change in the US data features is the smoothest of the three materials studied and occurs between seven and ten minutes. It was observed that the nature of the cleaning of malt was very different to the tomato and gravy. Although mechanical actions performed some role, it appeared from the images that the malt mainly dissolved into the water. Figure 7 presents numerous images from the two cameras between seven and ten minutes to determine which aspects of the fouling layer had the largest effects on the US reflected signals (Images 5-17 in Figure 7). During the first seven minutes the fouling layer appears to reduce in thickness (images 1-4 Figure 7) but no change is observed in the US results. This supports the argument that fouling layer thickness has little effect on the received US signals during the initial stages of cleaning, with the current US system. During the time periods where the US data features change, the images show that the largest change is the coverage area of the fouling material (Images 5-17 in Figure 7). This supports the argument that the US results are most sensitive to the area of fouling covering the transducer's active element area and not the fouling layer thickness. Ultrasonic transducers with larger active areas may therefore be more suitable for monitoring cleaning processes. However, practical challenges remain here as the active element area is usually determined by the frequency of the transducer, with higher frequency transducers preferred in thin walled systems to reduce the effects of overlapping signals (Equation 3). Larger diameter transducer may also have contact issues with small diameter pipework.

Fryer and Asteriadou presented two classification methods for cleaning problems. The first method was based on the fouling material type and the second on the cleaning mechanism (Fryer & Asteriadou, 2009). For the method based on the material type all of the fouling materials reported in this current work are type 1 (of the three types they specify). Type 1 fouling are defined as viscoelastic fluids, which can be rinsed from a process surface with water. For the second method based on cleaning mechanism the different types of cleaning were define as *fluid mechanical removal* and *diffusion reaction* removal. Fluid mechanical removal is the removal of surface fouling using the force provided by the fluid. From our results this appears to be the cleaning mechanism of the tomato and gravy. The results indicate that the US data features for this type of cleaning display a sudden change in the recorded US data features and some localised temporal changes as the material is been removed (Figures 5 and 6). Fryer and Asteriadou, 2009 define diffusion reaction removal as the diffusion of a chemical into the fouling material to aid in its removal. Although no chemicals were used in this current work the fouling removal of the malt appears to follow this concept as the water was dissolving the fouling layer. The US results for this type of cleaning, show a gradually changing curve with little or no localised variation in values. When comparing the three US data analysis methods it appears that all are suitable for detecting the presence of fouling and monitoring certain stages of cleaning. All three methods vary in the same time domains but the RMSE and US energy methods are preferable as they show the largest variation in results during cleaning, potentially making them more suitable for systems with a lower degree of fouling.

3.4 Repeatability and temperature effects

Figure 8 displays the US energy for repeat experiments for the three fouling materials at low (12 ℃) and high (45 ℃) temperature. All energy values returned to the same value of 1.9×10^{8} EU for the experiments at 12℃ and 2.1×10^{8} EU for the experiments at 45℃, once the fouling materials had been removed. This supports the earlier assertion that the developed US system can repeatedly monitor the cleaning of a range of different fouling materials at ambient and elevated temperatures. Of the six results presented in Figure 8 the only ones that did not consistently return to the same final energy value was the tomato at high temperature. These were the first experiments that were performed and it is likely that the contact between the transducer and the wall had not yet stabilised. The importance of having transducers that are either fixed in place or have been given enough time to form a stable contact before performing experiments cannot be overstated. The malt had the most repeatable cleaning profile with very little variation in cleaning time or data trends between runs (Figure 8). The malt cleaning experiments at higher temperature showed that surface fouling was removed in a much faster time of approximately two minutes compared to approximately 13 minutes for the lower temperature (Table 2). This supports the theory that the malt cleans by dissolving as it is known that dissolution occurs faster as higher temperatures due to the increase in kinetic energy. It has also been reported in the literature that temperature increases the cleaning rate of fouling from numerous experimental studies (Fryer et al., 2006).

The effect of temperature on cleaning time for tomato cannot be studied quantitatively as a lower flow rate was used for the high temperature experiments (Table 1). This lower flow rate was used as the tomato cleaned almost instantaneously at the faster flow rate and higher temperature. The gravy was difficult to clean with water at low temperature so only two repeats were performed. These two experiments had very different cleaning times of approximately 40 and 100 minutes. The results in Figure 8 and Table 2 indicate that cleaning processes, which are primarily dependent on mechanical forces for removal, appear to be much more variable than those dependent on dissolution.

4. Conclusions:

Cleaning of processing equipment is essential to ensure hygienic and optimal processing conditions within industries such as the food, pharmaceutical and FMCG. However, current CIP processes are often inefficient, over cleaning equipment, with significant negative financial and environmental impacts. In this work an US sensor technique capable of monitoring the cleaning of different food fouling materials was developed and experiments performed in a bespoke laboratory rig. It has been shown that the developed US technique was capable of monitoring the fouling removal of the three food materials, which all clean from the test section differently. It was shown that the US energy and RMSE of a windowed section of the received US signal were the most suitable data analysis techniques to use. Repeat experiments were performed at two temperatures (12℃ and 45℃) and almost identical values of the US data features were obtained at the end of each experiment, once the test section was cleaned. This demonstrates the potential of the US technique for a range of different fouling materials. The tomato paste was found to clean gradually mainly by mechanical force, the gravy swelled due to the presence of water and was removed in a single lump whereas the malt slowly dissolved into the water. The time to clean was relatively similar for repeat experiments of the malt but much more variable for the tomato and gravy. Analysis of the images and the US results indicated that variations in the US signals were more sensitive to the amount of fouling material within the area covered by the US transducer's active element than the fouling layer thickness. This indicates that the current technique may be limited in monitoring the initial stages of cleaning.

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