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Pooja Dubey, Nico Declercq

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A study on ultrasonic wave propagation and interaction with plate heat exchanger

P. Dubey ^{a,b} et N.F. Declercq ^{a,b}

^a Georgia Tech-CNRS IRL2958, Georgia Tech Lorraine, 2 Rue Marconi,
57070 Metz, France

^b School of Mechanical Engineering, Georgia Institute of Technology,
30332 Atlanta, Georgia, USA



Heat exchangers are an essential component in the food industry, power plants, water treatment, etc., and play a key role as heat-transfer devices. A plate heat exchanger is one of the most extensively used because it is economical, efficient, and flexible. It uses metal plates to transfer heat and has high heat transfer efficiency as the fluid is exposed to a larger surface area of the plate. However, the heat exchanging liquids in industries contain suspended or dissolved particles resulting in deposits over the plate, limiting heat transfer capability and thus reducing efficiency. Standard techniques such as chemical cleaning, manual cleaning, hydro-blasting, and steam blasting are widely used to handle this problem. However, they are inefficient and labour-intensive owing to drawbacks such as high handling risk, over-cleaning (which results in the loss of the protective oxide layer), and corrosion. The past decade has seen the rapid development of ultrasound-assisted heat exchangers to inhibit these deposits in the metal plates. Also, recent evidence proved it to be an efficient heat transfer enhancement technique. However, research on the subject has been restricted to investigating ultrasound efficiency to reduce deposition in the plate. Thus, this research aims to provide an experimental framework to understand the interaction of ultrasound waves with the complex structure of plate heat exchangers. The proposed research will help gain insight into the design strategy of a detection tool for fouling in heat exchanger.

1 Introduction

Heat exchangers are essential in the food industry, power plants, water treatment and play a crucial role as heat-transfer devices. A plate heat exchanger is one of the most extensively used because it is economical, efficient, and flexible. It uses metal plates to transfer heat and has high heat transfer efficiency as the fluid is exposed to a larger surface area of the plate. However, the heat exchanging liquids in industries contain suspended or dissolved particles resulting in deposits over the plate, limiting heat transfer capability and thus reducing efficiency. The deposition of these unwanted materials over the heat exchanger plates is commonly referred to as fouling. Thus, fouling is one of the major challenges with heat transfer devices [1].

Previous studies have reported using different mechanical and chemical mitigation methods for designing heat exchangers to reduce fouling in the plates [2]. A typical plate heat exchanger with a flow from the bottom left hole to the top right hole is as shown in Figure 1. Studies of crystallization fouling show that the scale formation pattern differs with increased CaSO₄ concentration, wall temperature, and flow velocity [3]. Thus, designing plate patterns with taking into account all the above factors becomes much more complicated.

In the past, a considerable amount of literature has been published mentioning the change in the geometry of the plates due to the deposition. Its effects include a reduction in the heat transfer efficiency and flow pattern [4]. Thus, a cleaning operation is implemented at predetermined intervals, in order to eliminate the fouling layer. This involves regular use of chemicals and a large amount of rinsing water. In addition, it takes several hours to clean per day, especially in the case of dairy industries. A visual inspection of the fouling effect is not possible in most of the industrial plants. However, the conventional methods used for detection involve the measurement of frictional pressure drop [5], deposit electrical conductivity [6-7].

Recent development in the field of acoustics led to the use of ultrasound-assisted heat transfer devices, which helps provide high heat transfer efficiency [8-10]. The research to date has tended to focus on investigating heat transfer efficiency using ultrasound waves rather than the detection of early-stage fouling in plates of the heat exchanger. However, only few research studies have been present to use

ultrasound as a detection tool. Most of them make use of transmission and pulse-echo methods to acquire properties of the material to gain insight into the plate quality. Despite this, a few research studies have relied on the detection of fouling with guided acoustic waves on pipes [11, 12].

There has been limited research to detect fouling in the heat exchanger. Prominent literature dealing with the issue suggests acoustic power and delay of the received acoustic wave as a parameter to monitor fouling in the plate heat exchanger. Its result shows a low-frequency ultrasound to be a promising real-time tool for fouling detection. However, it has been analysed that a change in the location of the sensors affects the results [13].

Furthermore, it uses a low-frequency probe which restricts the detection of small deposits. Thus, an investigation on the interaction of comparatively higher frequency ultrasound waves with the complex structure of patterned plate would provide a piece of instructive information about the use of different frequency ranges in designing an ultrasound-assisted heat exchanger or as a fouling detection tool for plate heat exchanger.

Thus, this preliminary research deals with the use of linear acoustics to understand the interaction of bulk acoustic waves with the titanium plate of the heat exchanger (Alfa-Laval, France). Further analysis on the same plate is carried out with the help of non-linear ultrasound. The paper concludes by mentioning the critical observation, drawbacks, and advantages of each technique used.

2 Materials and Method

The research investigates change in the linear acoustical parameters and nonlinear parameter for the heat exchanger plate with and without fouling.

Linear parameter under investigation includes shift in the amplitude and location of the time and frequency peak for the received signal for the transmission setup. Current research focus on propagation of ultrasound waves only through a single plate of a heat exchanger immersed in water.

Non-linear investigation includes the effect in the sensitivity of the Second Harmonic Generation (SHG) due to the presence of foulant.

2.1 Theory and Experimental methods

2.1.1 Linear Ultrasound Method

Ultrasound waves are extensively used as a non-destructive inspection technique in materials. Two types of ultrasonic waves that can exist in an isotropic or anisotropic solid are bulk waves and guided waves [14,15]. A transmission configuration using the bulk waves utilizes a pulser which emits ultrasound waves connected to the emitter transducer (1MHz) on one side of the plate.

The pulser sends pulses with a frequency of 1 MHz frequency and an input voltage of 250 V. The Polar C Scanner carries out a 2D scanning of the plate. The acoustic pressure waves interact with the plate and are transmitted and/or reflected. The transmitted pulse is received by another transducer of the same centre frequency (1 MHz). The receiver transducer is placed on the opposite side of the heat exchanger plate, as shown in Figure 1(b).

Figure 1(b) shows an experimental setup for the experiment. The time of arrival of the transmitted signal for both samples is analysed. Also, the corresponding amplitude of the time domain peak is plotted. Furthermore, the spectrum of the received signal by transducer is compared to monitor any change in the regions with fouling and without fouling.

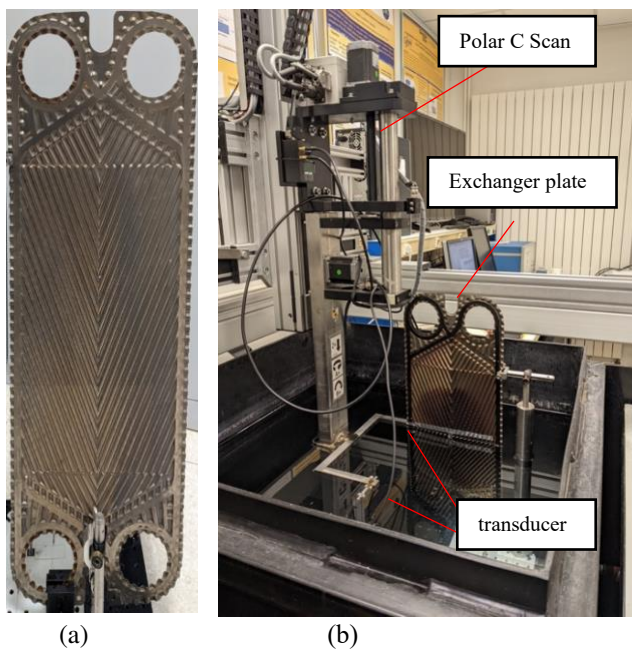


Figure 1 – (a) Image of a titane heat exchanger plate (b) Experimental setup for the linear ultrasound experiment showing the heat exchanger plate immersed in the water tank and emitter and receiver transducer to emit and acquire the signal, respectively.

2.1.2 Non-linear Ultrasound Method

SHG is one of the most widely used techniques to monitor microstructural damage in the material. Several

longitudinal studies have shown the excellent performance of the technique to detect the onset of microcracks in material with very small scale compared to linear ultrasound [16-18]. Thus, using non-linearity to measure the material property of the heat exchanger plate due to the deposition might be interesting research. Thus the interaction of the high input voltage ultrasound waves to the heat exchanger plate is analysed in the research. This will help to understand the capability of non-linearity parameters as a tool to detect fouling.

The method uses a sinusoidal input of frequency f interacting with the material. Due to the material non-linearities, the interaction generates higher harmonics. Thereafter, the non-linearity parameter relates the amplitude of the fundamental frequency to the second harmonic amplitude. Matlack et al. [19] provide the intuitive derivation of the parameter which is given by **Equation 1**.

$$\beta \propto \frac{A_2}{A_1^2 x} \tag{1}$$

Figure 2 shows the experimental setup of through-thickness investigation of longitudinal ultrasound waves using the SHG technique. A very high input voltage is provided to the transducer with the help of the RITEC system in order to visualize non-linear effect. For a 1 MHz sinusoidal input, the voltage obtained from RITEC is 760 p-p Volts (with gated amplifier gain of 50) and 1980 p-p Volts (with gated amplifier gain of 100). The high voltage input is fed to the transducer from the RITEC.

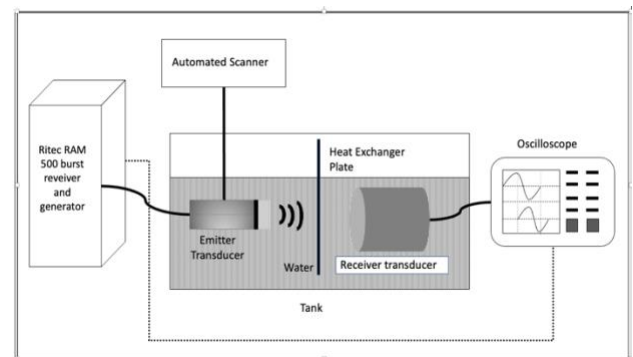


Figure 2 – Schematic for SHG through thickness setup with longitudinal waves to probe the heat exchanger plate.

2.2 Material

A heat exchanger plate made up of titan with a groove thickness of 4 mm is used for the experiments. A small area of 80mm x 10mm is considered for the investigation. The area under investigation is highlighted in red for the samples (fig 3(a) and fig 3(b)). Two samples are prepared to study the effect of the foulant. Sample 1 without a layer of foulant (fig 3 (a)) and sample 2 with a 4mm layer of foulant (paraffin wax) present in 50% of the area (position of wax starts approximately from $x = 40$ mm) (fig 3(b)). According to one of the promising pieces of literature, the use of paraffin wax to mimic an industrial deposit [20].

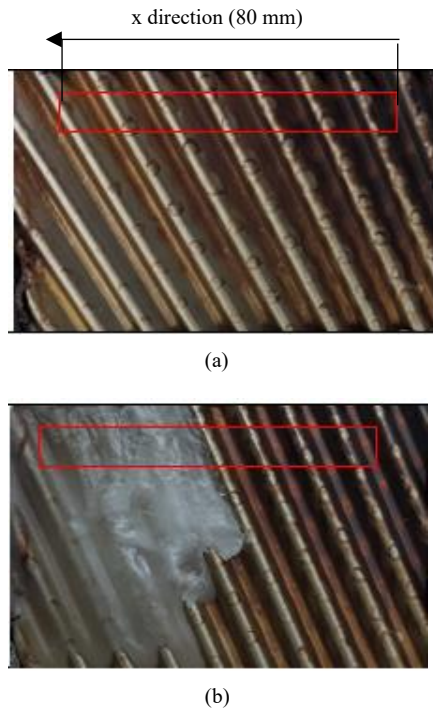


Figure 3 – (a) Sample 1 with no wax deposit on the heat exchanger plate. (b) Sample 2 with wax deposit on the heat exchanger plate. The highlighted area under investigation is 80mmx10mm with position x measured from right to left of the image shown by the arrow.

3 Results and Discussion

As expected, the peak amplitude of the received time-domain signal changes with a layer of wax. The change in amplitude is more than 60% (Figure 4(a)). However, the location of the time peak does not vary significantly, and the deviation was found to be approximately 0.27% (Figure 4(b)).

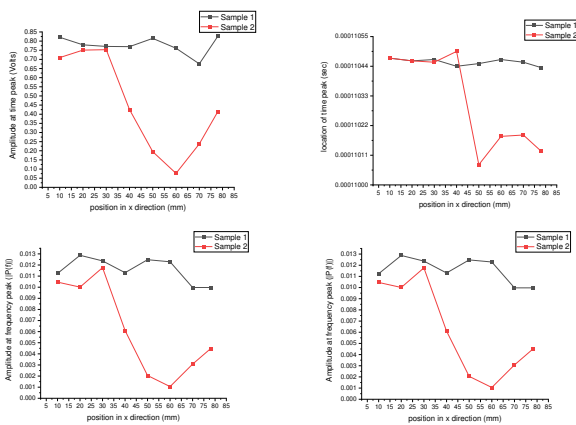


Figure 4 – (a) Time-domain plots showing the peak amplitude of the received signal (Top left) and (b) location of the time domain peak (Top right). Frequency domain plots showing (c) the amplitude of the frequency peak at 1MHz (Bottom left) and (d) the location of the corresponding peak (Bottom right) for sample 1 and sample 2.

The amplitude of the fundamental peak (1MHz) in the frequency spectrum shows a 27% decrease (Figure 4(c)). However, the location of the frequency peak was inconsistent in the region of wax deposition and deviated around 0.89 MHz to 0.91 MHz (Figure 4(d)). As predicted, the energy plot obtained depicts the reduction in the energy for sample 2 compared to sample 1.

To gain insight into the effect of ultrasound, the plots for the time signal, frequency spectrum, and time-frequency for sample 2 at point 10mm (without wax) and 70 mm (with wax) are plotted in Figure 5 and Figure 6, respectively and compared.

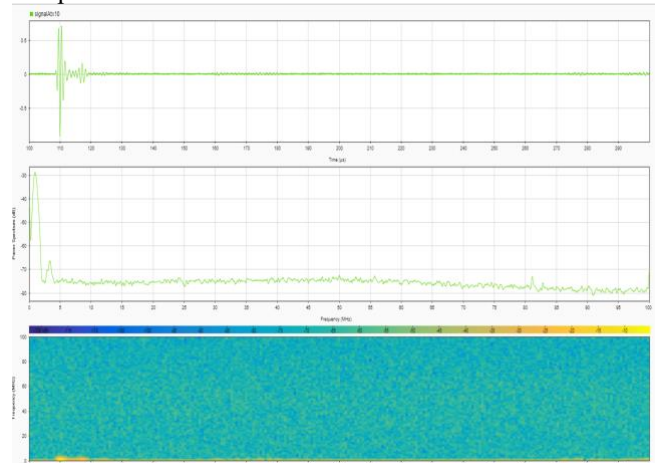


Figure 5 – Linear investigation plots showing the time signal, frequency spectrum and time-frequency plots for point at 10 mm (without wax region) for sample 2

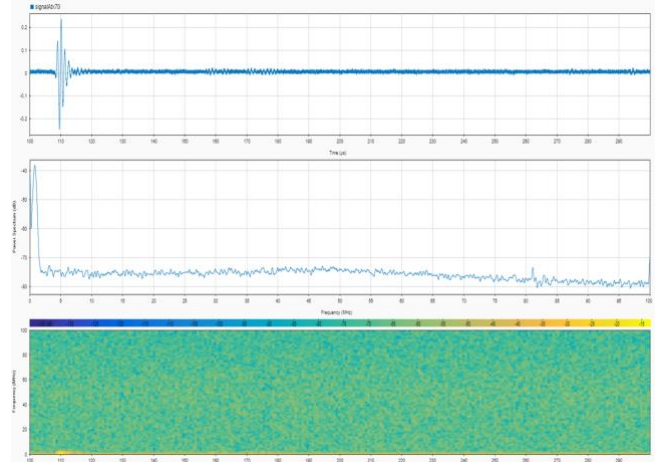


Figure 6 – plot shows the time signal, frequency spectrum, and time-frequency plots for point at 70 mm (with wax region) for sample 2.

Figure 5 and Figure 6 show that a significant change is not visible in the frequency spectrum and on the time-frequency plots for different regions. In contrast, the non-linear investigation shows a significant change in the frequency spectrum for the two regions (Figure 7 and Figure 8). The plots show a significant change in the second harmonic and fourth harmonic with the presence of wax. An interesting

phenomenon is observed relating to the sudden decrease in the second harmonic amplitude for the region with deposition (Figure 9).

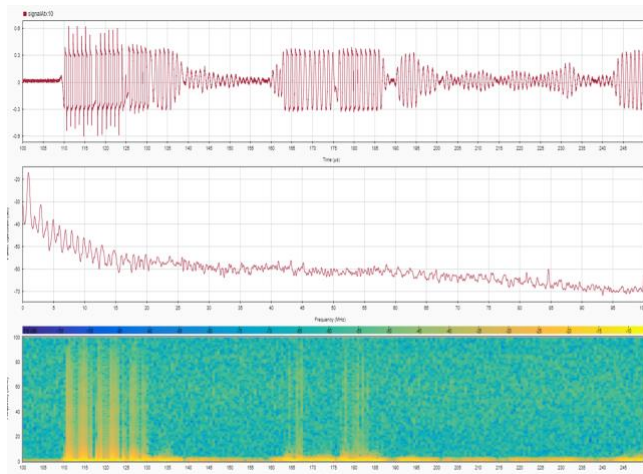


Figure 7 – Plots shows a non-linear investigation for an input voltage of 760 p-p Volts. From top to bottom: time signal, frequency spectrum, and time-frequency plots for the point at 10 mm (without wax region).

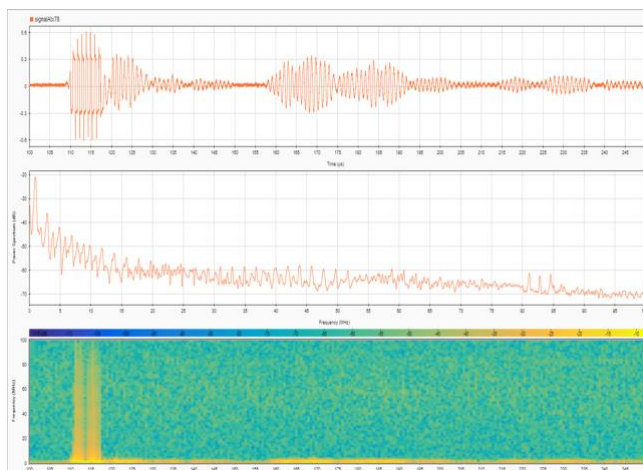


Figure 8 – Plots shows non-linear investigation for input voltage of 760 p-p Volts. From top to bottom : time signal, frequency spectrum and time frequency plot for point at 70 mm (without wax region)

In addition, the SHG technique shows a significant decrease in the non-linearity parameter (B/A) due to the presence of wax in the plate (Figure 10). The decrease in B/A is estimated to be roughly 67.85% for the input voltage of 760 p-p. A similar calculation for higher input voltage (1980 p-p) seems consistent with the previous value and is estimated to be 69.23% (Figure 11).

Although with the linear ultrasound results, the deviation in the signal amplitude is significant for deposition, this might vary based on the damping effect of the material for different types of foulant and is yet to be analysed. In contrast, non-linear ultrasound proves more convincing and consistent, as evident from the plots. It is observed that B/A proves to be a better tool for detecting the layer.

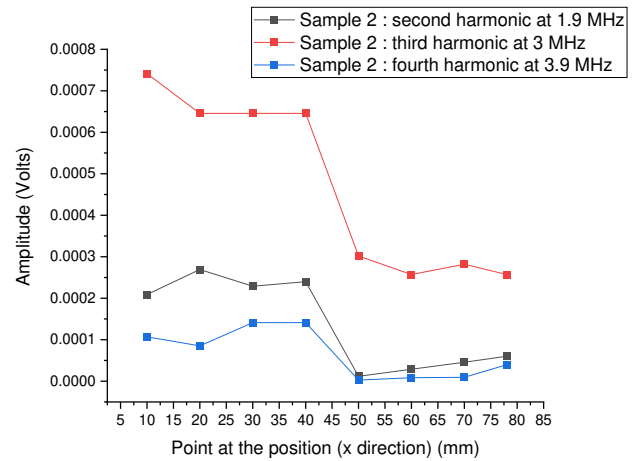


Figure 9 – Amplitude of second, third, and fourth harmonic with input a voltage of 760 p-p Volts showing a decrease in the amplitude with the presence of the layer.

However, a further analysis to account for the deviation in B/A with different thickness of the wax layer is still ongoing.

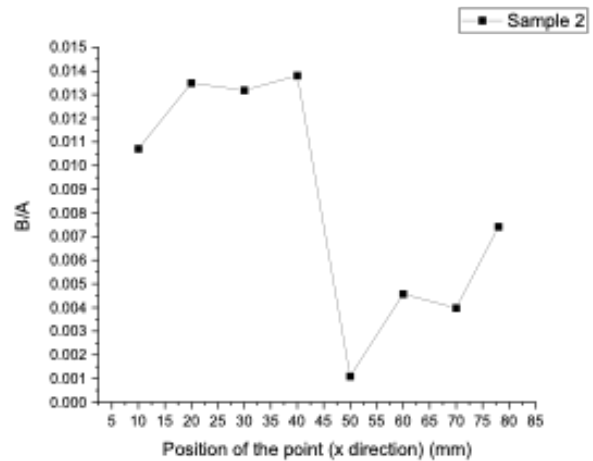


Figure 10 – Calculated B/A for different x positions of the sample 2 with an input voltage of 760 p-p Volts.

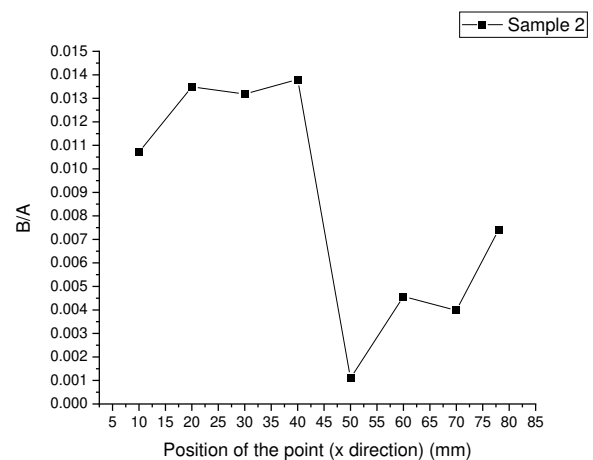


Figure 11 – Calculated B/A for different x positions of the sample 2 with an input voltage of 1980 p-p Volts.

4 Conclusion

The study presents an experimental analysis of the interaction of ultrasonic waves with a heat exchanger plate. It demonstrates the potential of several ultrasound techniques to explore the ultrasound-assisted heat exchanger. The research provides insights into the sensitivity of B/A parameter due to the presence of the foulant in the heat exchanger plate. The results further demonstrate that the effect in the non-linearity parameter is more significant than the computed parameters using linear ultrasound. The study paves the way to understand the more complex interaction of ultrasound with an actual arrangement of fouled plates in the heat exchanger.

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