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USING ACOUSTIC PULSE REFLECTOMETRY FOR QUALITY CONTROL OF HEAT EXCHANGER CLEANING

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ABSTRACT

Fouling in tube and shell heat exchangers is an acknowledged problem, hindering heat exchangers' efficient operation. Heat exchangers are therefore routinely cleaned at turnaround periods, though until recently there was no convenient method to "close the loop", i.e. evaluate the fouling quantitatively and verify the internal state of the tubes after cleaning. Acoustic Pulse Reflectometry (APR) has proved to be a very useful tool for this purpose. APR combines a very short inspection time (~9 seconds per tube) with the ability to quantify fouling using several metrics. Thus an entire heat exchanger or a representative sample of tubes can be examined before, during and after cleaning, in order to obtain a precise picture of the residual fouling and ensure this process is carried out satisfactorily, in the shortest time possible.

INTRODUCTION

Fouling of heat exchanger tubes can drastically reduce heat exchangers' efficiency, due to impaired heat transfer through the tube walls as well as reduced flow rates through the tubes. Many different cleaning methods are often employed to remove fouling, depending on the operating environment of the specific heat exchanger and the typical mechanisms of fouling in such environments.

For the cleaning process to be effective, it should be controlled and monitored properly, therefore ensuring the desired degree of cleanliness has been attained. Currently, the main technique available for determining cleanliness is visual inspection, which is slow and qualitative. Despite the fact that plants may have standardized cleaning procedures and contractual requirements specifying cleaning quality levels, these are not backed by applicable inspection methods.

Acoustic Pulse Reflectometry (APR) has emerged recently as a very fast and effective method for inspecting heat exchanger tubes, demonstrating high sensitivity to variations in cross section (Amir et al., 2010). This makes it extremely suitable for assessing the internal cleanliness of such tubes.

This paper presents the results of an experimental work conducted at an oil refinery, with the purpose of evaluating APR as a quality control tool for the inspection of heat exchanger tubes cleaned by a water jet.

The main conclusion of this work is that APR is capable of quantitatively evaluating cleanliness, and can easily demonstrate the differences in effectiveness of different cleaning protocols. Thus it can be applied to the validation of cleaning processes and procedures as well as for the formulation of specifications and contractual cleanliness requirements

BASICS OF APR

The principles of APR have been well known for at least several decades, with varied applications in academic laboratories, from reconstructing the bore of brass wind instruments to leak detection in various types of pipes and tubes (Amir et al., 1995; Sharp et al., 1997). Several industrial applications have been examined also by the present authors and others (Quirk, 1998; Papadopoulou, 2008; Amir et al., 2010).

The basic concept behind APR is to inject a wideband acoustic pulse into the medium inside a tube – air, in this case. This pulse acts as a form of "virtual probe." As long as the pulse encounters no discontinuities, it continues to propagate down the tube. Whenever a discontinuity is encountered, such as a blockage, expansion (due to wall loss, for example) or hole – a reflection is created. The reflected waves propagate back down the tube where they are recorded and stored on disk.

The different discontinuities enumerated above have different signatures, which are shown schematically in Figure 1. In heat exchanger tubes, any such discontinuities are caused by defects.

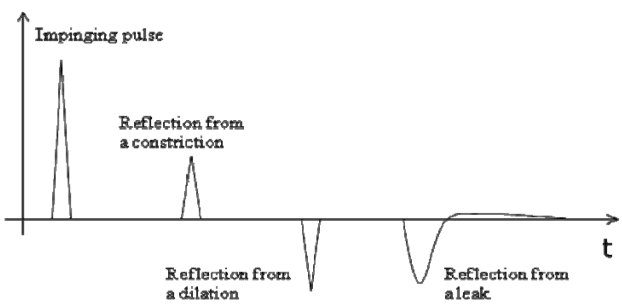

Fig. 1 Schematic examples of reflections from discontinuities

APR is very well suited to tube inspection for several reasons. First, the pulse acting as a probe travels through the tube at the speed of sound, resulting in inspection rates much faster than those possible with other techniques. Measurement of a single tube takes only several seconds, and there is no physical probe to push through the tubes or become stuck. In addition, the resultant measurements can then be analyzed by appropriate signal processing software which is potentially faster and more objective than human analysis.

Use of APR to detect fouling

When applying traditional tube inspection methods such as eddy-current or ultrasound, the tubes must necessarily be traversed by a probe. In such cases, the disturbance caused by fouling can range from a minor annoyance in light cases, to the point where it precludes any possibility of inspection, in the heavier cases. When applying APR, however, randomly distributed fouling appears simply as a multitude of blockages of different sizes. To see how this shows up in the APR signals, consider first Figure 2, which shows a comparison between a measurement of a clean tube and a measurement from a tube with a major blockage. While the measurement from the clean tube contains only background noise, the measurement from the blocked tube shows a

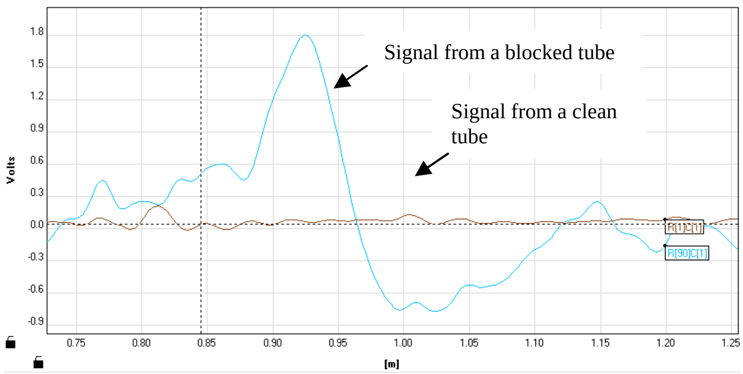

Fig. 2 Signals taken from a clean tube and a blocked tube

positive peak where the blockages starts (indicating a reduction in cross section) and a negative peak where the blockage ends (indicating an increase back to nominal cross section).

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While this is typical of isolated blockages, heavy fouling along the tube will be indicated by multiple overlapping positive and negative peaks, which tend to appear more like a very noisy signal rather than the one in Figure 2. An example of several such signals is shown in Figure 3.

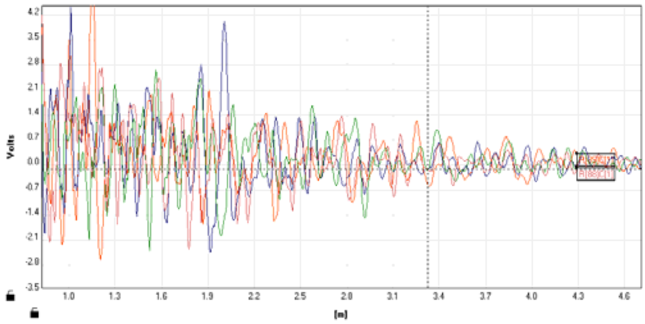

Fig. 3 Several signals taken from heavily fouled tubes

In the case of isolated blockages, a straightforward method can be used for determining their size. Since accurate theoretical models are available for simulating blockages [2], actual peak heights can be compared to theoretically calculated thresholds in order to determine what percentage of the cross section is blocked. For example, overlaying a set of thresholds on the blockage in Figure 2, as shown in Figure 4, the peak can be seen to cross the threshold indicating a blockage of 75%. The thresholds can be seen to decay exponentially as distance from the inlet increases, due to the attenuation of the pulse and its ensuing reflections.

In the case of multiple blockages caused by heavier fouling, some kind of averaging over a multitude of tubes is more informative than sizing of individual blockages. This can be obtained by taking an ensemble of measurements, possibly measuring all tubes in the heat exchanger, and plotting the Standard Deviation (SD) of all measurements at each point along the signal. From our experience, multiplying the SD by four usually give a visual representation that roughly matches the envelope that would be obtained by connecting the peaks. We therefore define the "noise band" as the lines that delineate 4 SD's above and below zero on the Y axis. An example of multiple signals and their noise band is shown in Figure 5, along with the blockage thresholds. The noise band varies between the 15% and 25% thresholds. Several isolated blockages can be seen to be much larger than the average.

For comparison Figure 6 shows 33 signals from measurements on a new heat exchanger. Since the tubes are clean in this case, the noise band is very narrow, not crossing the 1% blockage threshold, and no isolated peaks are present.

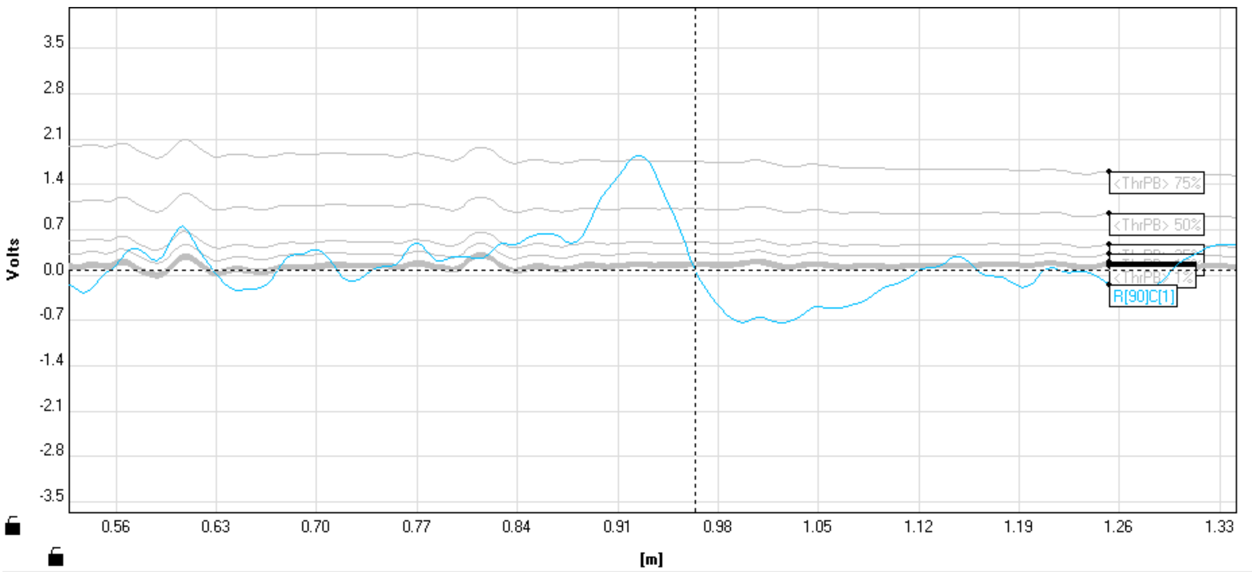

Figure 4 - A signal with a single blockage, along with thresholds (light grey) for determining blockage size

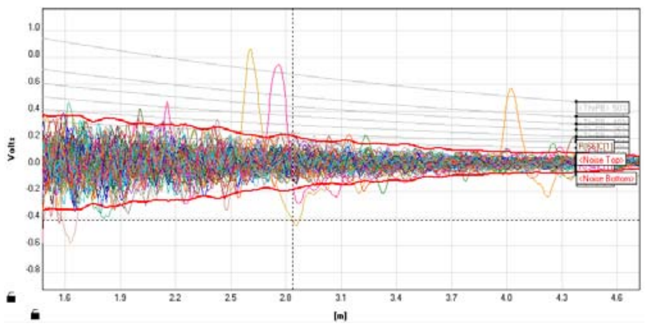

Fig. 5 Superimposed signals from 94 heavily fouled tubes, along with the resultant noise band, and the calculated blockage thresholds.

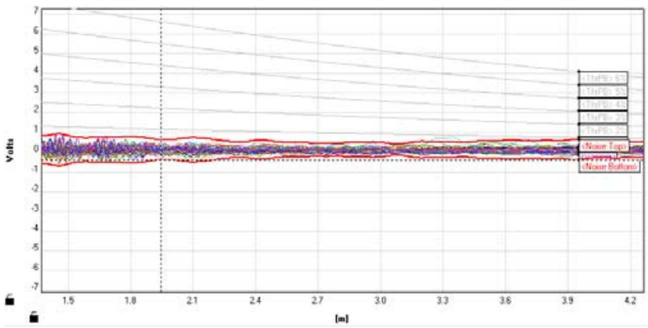

Fig. 6. Superimposed signals from 33 clean tubes, along with the resultant noise band, and the calculated blockage thresholds. The noise band is very narrow in this case.

The graphical and quantitative tools above enable an accurate estimate of fouling that could be used to quantify it at various stages of the cleaning process. To verify this, we conducted a carefully controlled experiment, as detailed in the next section.

EXPERIMENTAL PROCEDURE

A shell and tube heat exchanger at a large refinery was taken out of service for cleaning, inspection and retubing. Cleaning was carried out manually, using water jets. The process consisted of three phases: 1) a preliminary phase intended to dislodge encrustations adhering to the internal tube surface, by means of traversing a probe applying 7-8 KSI water jets in a direction normal to the tube axis; 2) a main phase in which a water-jet gun injected a 7.5 to 10 KSI water-jet in a longitudinal direction into the tube; 3) the last phase, applying low pressure water to wash out any residual contaminated water.

The normal procedure at the refinery was to apply stage (2) at 7.5 ksi for 10 seconds. In this experiment we controlled stage (2) by varying the applied pressure and the time of application of the jet. We applied two pressure levels – 7.5 and 10 ksi – and four cleaning cycle-times – 5, 10, 20, and 30 seconds per tube. After the cleaning process, the tubes were air blasted in order to rid them of any residual water that could cause artifacts in the subsequent APR measurements. All measurements were conducted on different groups of tubes in the same heat exchanger, as we assumed that before cleaning, the level of fouling was initially uniform throughout.

The results were then analyzed and quantified as detailed below.

Defining quantitative measures of fouling

Two quantitative measures were extracted from the APR signals in order to assess the degree of cleanliness: (i) the number of tubes having a blockage above a predefined threshold, in this case 50% and 75% of the cross-section; and (ii) the width of the noise band, measured with respect to the highest blockage threshold it reached.

RESULTS

Table I shows the above quantitative measures for the different cleaning cycles. As seen in the second row, skipping phase (2) altogether leaves heavy fouling in the tubes, with a noise band of 20% and many blockages over 50% and 75%. The process marked as "Std." was the standard procedure, as applied by the cleaning contractor on a group of tubes before our arrival on site. Evidently, it left a large degree of fouling, since the noise band was still very wide (25%), though the percentage of extreme blockages was reduced.

Table 1. Summary of quantitative measures for each type of cleaning cycle

Process	*Press. [ksi]*	*Cycle time*	*Sample size*	*Noise band [% of block]*	*Tubes blocked >50% [%]*	*Tubes blocked >75% [%]*
New tubes	-	-	32	<1	0	0
No phase 2	-	-	115	20	26	11.3
std.	7.5	10	94	25	13.8	3.2
A.	7.5	5	53	20	3.8	3.8
B.	7.5	20	61	15	3.3	0
C.	7.	30	67	10	3	0
D.	10	5	71	12	1.4	0

Varying the duration of the main phase from 5 seconds to 30 seconds in a controlled manner (rows A to C), while maintaining a jet pressure of 7.5 KSI, clearly resulted in progressively cleaner tubes, reducing both the noise band and the number of tubes with extreme blockages. Interestingly, increasing the jet pressure to 10 KSI, while reducing the main cycle to only 5 seconds (row D), also gave good results, on par with the much longer cycle (30 seconds) at 7.5 KSI. Several representative graphs are shown in Figures 7-9.

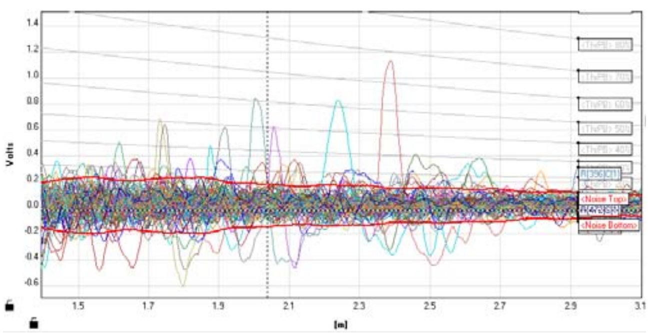

Fig. 7. 115 superimposed signals after partial cleaning, i.e. no main phase. Note the many isolated peaks.

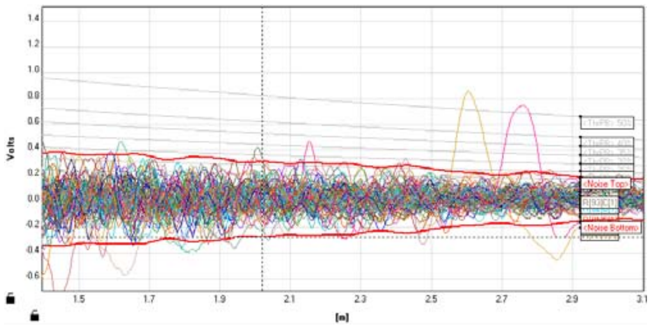

Fig 8. 94 superimposed signals after "standard" cleaning. Noise band is still wide, but fewer isolated peaks are present.

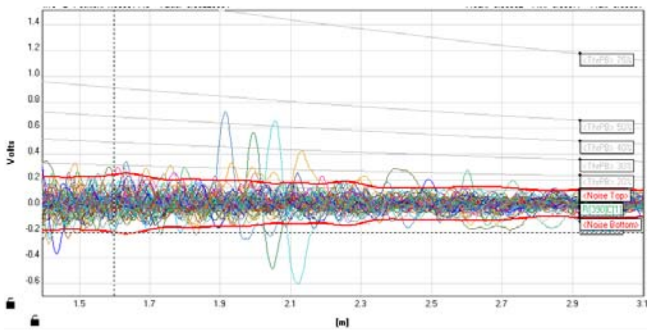

Fig. 9. 71 superimposed signals after cleaning with 10 ksi. Noise band is narrower with few isolated peaks.

DISCUSSION AND CONCLUSIONS

From the results presented above, it is clear that APR can provide a quantitative estimate of the degree of fouling in a heat exchanger. There are several ways in which the raw information from the individual APR signals of each tube can be integrated to obtain the "big picture" describing the condition of the entire heat exchanger. In this paper we presented two such methods: counting individual blockages above a set threshold and calculating the variance at each distance over the entire ensemble of measurements. Both methods provided complementary data, though other analyses could be applied also. Currently there is no other technique to quantify heat exchanger fouling, so this has not been explored exhaustively, and should probably be looked into in collaboration with operators, in order to determine which parameters are most relevant to the maintenance of their individual heat exchangers.

Important advantages of APR are that it gives a clear indication of fouling throughout each inspected tube, without the risk of stuck probes and without a need for visual interpretation by an expert operator. Furthermore, the short inspection time per tube ensures that it does not introduce lengthy delays into the maintenance process.

Overall, it is conceivable that APR would be applied in several complementary instances:

1. To assess the initial condition of the heat exchanger before cleaning. This could give a

picture of the degree of fouling to be expected after a set period of running the heat exchanger.

2. As a useful tool to assess the effectiveness of different cleaning processes in order reach the most efficient cleaning protocol. Further comparisons similar to the experiment conducted above could determine the most cost effective or time effective methods of cleaning, which would probably be heavily dependent on the application.
3. As part of the contractual agreement with a service provider carrying out the cleaning, used as an objective measure to verify this process. We have found this to be a sore point in some instances. In extreme cases, we found that cleaning contractors had left large segments of heat exchangers that had not been cleaned at all, without the operator having any knowledge of this.

Limitations and further work

In theory, APR can detect any isolated change in cross section, however miniscule. In practice the detection capability is limited first by the background noise, whether ambient acoustic noise or shot noise in the electronic components such as the amplifiers and A/D elements. A robust implementation of this technology should ensure a high degree of immunity to noise through the use of appropriate excitation signals. In the present case, an MLS signal was used, as described elsewhere in more detail (Amir et al., 2010). In laboratory conditions, this enabled detection of changes in cross section of less than 1%, though the absolute lower limit was not determined, as we found no need to. This limit can be determined by carefully controlled experiments if necessary. A further confounding factor that introduced unexpected "noise" into the measurements in some cases, even in clean tubes, was due to the variability in the internal cross section of the tubes. This is inherent to the actual manufacturing process, therefore different types of tubes exhibited this phenomenon in different degrees. In our experience, aluminum tubes were found to be most uniform, whereas in stainless steel tubes the fluctuations were considerable.

A second limitation on detection capability is imposed by the wavelength of the highest frequency in the excitation signal. This determines the duration of the acoustic signature, which may overlap with reflections from adjacent blockages. This problem crops up mainly when there is importance attached to the accurate sizing of closely spaced blockages. In the measurements presented here, the highest frequency was about 6kHz, having a wavelength of approximately 6 cm. This can be shown to give an axial resolution of approximately half the wavelength, 3cm. In applications related to fouling this is not a major limitation, since the sizes of individual blockages are less important than the overall picture obtained from statistical analysis over the entire set of tubes.

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