An investigation on using electrical resistance tomography (ERT) to monitor the removal of a non-Newtonian soil by water from a cleaning-in-place (CIP) circuit containing different pipe geometries

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**Abstract**

This paper presents a feasibility study of employing electrical resistance tomography (ERT) technology for monitoring water based cleaning-in-place (CIP) processes. Specially designed 1.5 in transparent Perspex pipes of different geometries, fitted with multiple planes of inline ERT probes, were filled with a non-Newtonian shampoo product, and then cleaned by flushing fresh tap water through at different flow rates ranging from 4000 to 8000 kg/h. The maximum pixel conductivity, defined as the maximum of the reconstructed 316 pixel conductivities in each ERT frame, was proved to be a sound and robust cleaning process monitoring indicator. The investigation demonstrated that the ERT technology is capable of shedding more detailed insights into the CIP process than any other monitoring technologies currently being employed.

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1. Introduction

Cleaning-in-Place (CIP) refers to a method of using a mix of chemicals, heat and water to remove deposit layers, or ‘soil’, from the interior surfaces of pipes, vessels, process equipment, filters and associated fittings, without dismantling. A typical CIP process may consist of hundreds of metres of pipe work, a multitude of valves, pumps and instrumentation, and consume large amounts of water, chemicals, and energy. In a fruit jam manufacturing facility in Manchester, UK, for example, cleaning hoses in the fruit room were identified as one of the highest end uses of water in the facility (17% of total site water consumption) (Brush et al., 2011). Although the definition of ‘cleanliness’ can vary from industry to industry, the needs to have a CIP procedure that is effective, reproducible, controllable, and verifiable are common to all. This is especially true for industries of fast moving consumer goods (FMCG), where products have a relatively short life cycle, but high levels of hygiene must be maintained at all times.

In the cosmetics and personal care industry, a manufacturing plant must be cleaned and disinfected for every change of product to ensure regulatory compliance and sanitation standard adherence. The CIP process involved normally consists of a water based, two-step (hot water, followed by deionised water) operation (Kaya and Arayici, 2009). Despite being a relatively simple CIP process, and cleaning being
monitored by the implementation of a combination of localised and integrated sensing technologies, including turbidity, light diffraction, conductivity, temperature and pressure drop etc., determinations of the cleaning ending point and root causes to fouling remain difficult (Wilson, 2003; Martin et al., 2013; Cole et al., 2010). Most of the integrated sensing methods, such as pressure drop or heat transfer, would fail to provide sufficiently sensitive information for local variations especially when the cleaning approaches the designated ending point. For localised sensing methods, e.g., conductivity, turbidity, and light diffraction, identifying representative sensor installation or sampling locations (sites of worst fouling) has been a longstanding problem (Hasting, 2002; Van Asselt et al., 2002).

Although the technology advances in modern instrumentation have enabled a cleaning process to be probed to much greater details than ever before, the lack of an effective and practical inline sensing system that can meet all the industrial requirements remains one of the primary challenges facing the CIP industry (Wilson, 2003; Fryer and Asteriadou, 2009). Crucially, industry requires that:

1. the progress of the whole cleaning cycle, from the beginning of the deposition layer undergoing to the removal of the last remaining fragment, can be measured and monitored continuously, so that the right cleaning operation can be carried out at the right time, location, and conditions;
2. the cleaning ending point can be identified and validated to the required sensitivity and accuracy, so that the ‘proof of clean’ is assured, and at the same time the production downtime and environmental impact of cleaning is minimised;
3. the data generated from the sensing system can be readily interpreted by the controlling computers, and linked to hazard analysis and critical control points (HACCP) analysis, so that appropriate corrective actions can be promptly initiated through key ‘performance indicator’ checking.

To date, none of the monitoring techniques or sensing systems currently available has been able to operate even close to meeting all those requirements. As a result, CIP systems are largely designed without knowing where the sites of worst fouling are located, so need to be monitored closely, and CIP protocols are largely established and operated without knowing when cleaning has reached designated ending points.

In this paper, we aim to investigate whether the electrical resistance tomography (ERT) technology (Beck and Williams, 1995) could be used as an effective in situ and real-time tool for monitoring water based CIP processes. Specially designed transparent Perspex pipes of different geometries, fitted with multiple planes of inline ERT probes, were filled with a non-Newtonian shampoo product, and then cleaned by flushing fresh tap water through at different flow rates. The principal objective of the investigation was to see whether a universal cleaning performance indicator could be formulated from the ERT sensing data, which could be readily incorporated into the controlling software to enable automated decisions to be made to identify:

1. the ending points of the shampoo cleaning process;
2. the geometry of worst fouling, i.e., the most difficult to clean geometry of all the pipe geometries tested;
3. the site of worst fouling in each geometry, i.e., the most difficult to clean spot or region of any given pipe geometry tested.

2. ERT: relevant background and system details

ERT is a non-intrusive imaging technique, in which the internal compositions or electrical properties of a domain can be ‘constructed’ through electric current injections and voltage measurements along the boundary of the domain (Scott and McCann, 2005). The ability of the technology to ‘see’ inside an optically inaccessible object or domain without employing intrusive probes, offers tremendous advantages over other monitoring or sensing methods. ERT has been used as a unique tool in a wide range of engineering areas for medical diagnosis, process monitoring and control, reactor and vessel characterisations, unit operation analysis, and simulation verifications (Brown, 2003; Sharifi and Young, 2013; Bolton and Primrose, 2005). Use of ERT for CIP process monitoring, however, has been a relatively new concept, and publications remain scarce. In 2007, Henningsson et al. (2007) reported the first case study, in which ERT measurements were performed in a diary processing plant in Sweden to verify the CFD simulation results on the removal of yoghurt by water from a simple Ø60 mm ID straight pipe section. Good agreements were observed between the measured data and predictions in terms of the time dependency behaviour for different process conditions.

The ERT probes used in the currently investigation consist of multiple electrode planes, each made of 16 M5 threaded stainless steel rod electrodes, arranged at equal interval around pipes of different geometries being investigated. The electrodes were flush with geometries’ inner surface, thus in contact with the process fluid. Fig. 1 shows a photo image of three electrode planes mounted on a 1.5” straight pipe section. A commercialised ERT instrument system, ITS-P2000 (Industrial Tomography Systems, Manchester, UK), together with the ITS P2+ software (version 7.3) was employed for data acquisition and image reconstruction. The instrument permits only the adjacent drive pattern (Bolton and Primrose, 2005), in which a small alternating current (5 mA at 9600 Hz in the current case) is applied through a pair of neighbouring electrodes, and voltages are measured from all the other
neighbouring electrode pairs, excluding the current injection pair and two pairs adjacent to it (Fig. 2(a)). The current injection then rotates to the next neighbouring electrode pair in the clockwise direction, and voltage measurements are repeated, until all the neighbouring pairs have been covered by the current injection. Taking the reciprocal theorem into consideration (Wang et al., 1999), a 16 electrode plane would generate 104 independent boundary voltage measurements.

Image reconstruction was conducted via the built-in functions in the ITS P2+ software. For each electrode plane, the software discretises the circular domain into 316 square pixels. A non-iterative linear back-projection (LBP) algorithm is employed to ‘recover’ the conductivity values within those pixels based on the current injection magnitude and 104 boundary voltage measurements (Polydorides, 2002).

For sensitivity theorem based 2-D ERT image reconstruction algorithms, the core mathematical expression can be written as (Wang, 2002):

\[
\frac{\Delta v_j}{v_{R,j}} \approx \sum_{k=1}^{w} \Delta \sigma_k s_{j,k}
\]

in which \(j = 1, 2, \ldots, p\), is the location of the voltage measurement projection (in the current case, \(p = 104\)); \(k = 1, 2, \ldots, w\), is the pixel number (in the current case, \(w = 316\)); \(s_{j,k}\) is the sensitivity coefficient at the \(k\)th pixel under the \(j\)th measurement projection; \(v_{R,j}\) and \(\Delta v_j\) denote the reference voltage and voltage change at measurement projection \(j\) respectively; while \(\sigma_{R,k}\) and \(\Delta \sigma_k\) denote the reference conductivity and conductivity change at pixel \(k\) respectively.

Since the reference frame is always taken from a uniformly distributed medium with a known conductivity, then \(\sigma_{R,k}\) is a constant for all the \(k\). In the current case, tap water was taken as the reference frame, so \(\sigma_{R,k} = \sigma_R = 0.1\) mS/cm.

Consider the following normalisations:

\[
u_j = \frac{\Delta v_j}{v_{R,j}} = \frac{v_{M,j} - v_{R,j}}{v_{R,j}}
\]

\[
\sigma_k = \frac{\Delta \sigma_k}{\sigma_R} = \frac{\sigma_{C,k} - \sigma_R}{\sigma_R}
\]

\[
s_{j,k} = \frac{s_{j,k}}{\sum_{k=1}^{w} s_{j,k}}
\]

where \(v_{M,j}\) and \(\sigma_{C,k}\) are the voltage measured at projection \(j\) and conductivity to be ‘recovered’ at pixel \(k\) respectively for a specific frame. Eq. (1) can be written into the following matrix form:

\[
\begin{bmatrix}
    v_1 \\
    v_2 \\
    \vdots \\
    v_p \\
\end{bmatrix}_{p \times 1} \approx \begin{bmatrix}
    S_{1,1} & S_{1,2} & \cdots & S_{1,w} \\
    S_{2,1} & S_{2,2} & \cdots & S_{2,w} \\
    \vdots & \vdots & \ddots & \vdots \\
    S_{p,1} & S_{p,2} & \cdots & S_{p,w} \\
\end{bmatrix}_{p \times w} \begin{bmatrix}
    \sigma_1 \\
    \sigma_2 \\
    \vdots \\
    \sigma_w \\
\end{bmatrix}_{w \times 1}
\]

The above equation describes the basic principle of the ERT system. For circular electrode ring configurations, the sensitivity matrix \(S_{j,k}\) can be calculated either analytically or numerically via the finite element method (FEM) (Wang et al., 1993; Mura and Kagawa, 1985). Sensitivity matrices for 8 or 16 circular electrodes have already been included in the ITS P2+ software.

To reconstruct an image of conductivity distribution in the circular measurement plane, the inverse problem has to be solved. This can be written directly in a simplified form as:

\[
\sigma = -S^{-1}v
\]

However, the inverse of the sensitivity matrix in general does not exist, as the sensitivity matrix is normally ill-conditioned. As a result, the solution would have to be obtained through the introduction of the pseudoinverse concept (Dyakowski et al., 2000):

\[
\hat{\sigma} = -\hat{S}v
\]

in which \(\hat{\sigma}\) is the approximation to the real solution \(\sigma\), and \(\hat{S}\) is a modified sensitivity matrix that represents the inverse of \(S\).

A variety of algorithms have been proposed to construct \(\hat{S}\) (Polydorides, 2002; Yorkey et al., 1987; Chen, 1990). The current investigation used the linear back projection (LBP) algorithm, in which \(\hat{S}\) is taken as the transposed sensitivity matrix (Yorkey et al., 1987):

\[
\hat{S} = S^T
\]
Fig. 3 – The rheological property of the shampoo product at 15 °C, used as the ‘soil’ material in the current investigation.

Thus, the image reconstruction involves only a single matrix-vector multiplication:

\[
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\vdots \\
\sigma_w \\
\end{bmatrix} = 
\begin{bmatrix}
S_{1,1} & S_{1,2} & \ldots & S_{1,w} \\
S_{2,1} & S_{2,2} & \ldots & S_{2,w} \\
\vdots & \vdots & \ddots & \vdots \\
S_{p,1} & S_{p,2} & \ldots & S_{p,w} \\
\end{bmatrix}^T
\begin{bmatrix}
v_1 \\
v_2 \\
\vdots \\
v_p \\
\end{bmatrix}_p 
\]

(9)

LBP offers distinctive advantages of being a numerically simple and computationally fast algorithm. However, the quality of reconstructed images is relatively low. In most cases, it can only be considered as a qualitative algorithm.

Fig. 2 shows a schematic illustration of the adjacent current injection pattern for a circular 16 electrode configuration, the 316 square pixels representing the circular cross-sectional domain, and a reconstructed tomogram of conductivity profile within the domain.

3. Experimental configurations

3.1. Materials

A basic shampoo product, which is in a surfactant structured mesophase, was used as the ‘soil’ material. Fig. 3 shows a flow curve of this product at 15 °C, measured on a cone and plate AR2000 rheometer (TA Instruments, USA). The data demonstrate a typical Non-Newtonian inelastic fluid behaviour – nonlinear without intercept. The flow behaviour has stayed unchanged throughout the duration of this project.

Tap water was used as the cleaning agent. All experiments were conducted at 15 °C. This was the temperature which could be realistically controlled without employing large scale heating facilities and, in addition, the Perspex sensors used in this study were not tolerant of typical industrial CIP temperatures.

3.2. Experimental setup

Fig. 4 shows a piping and instrumentation diagram (P&ID) of the experimental setup. The main experimental circuit comprised of 1.5” nominal size stainless steel pipes coupled by inline (ILC) fittings. Shampoo was first slowly introduced into the CIP-ERT unit from a 65 L double-jacketed vessel. Care was taken to make sure that the CIP-ERT unit was wetted and completely filled with the shampoo. Cleaning then started with water being introduced from the 3.5 m³ water sump at the desirable flow rate to flush through the shampoo filled CIP-ERT unit. Apart from the use of a 3” Worthington-Simpson centrifugal pump, the water flow rate could also be boosted to 8500 kg/h by switching on a Silverson 150/250 In-line Mixer running at 9800 rpm.

The CIP-ERT unit consists of two sections, a straight 1.5” Perspex pipe section fitted with 3 planes of 16 inline ERT electrodes (Fig. 1), followed by a tailor-designed Perspex test pipe section containing test pipes of different geometries, each also fitted with multiple 16 inline ERT electrode planes around the pipe circumference. The 16 electrodes in each plane were all made from MS threaded stainless steel rods. This is not only the maximum number of electrodes that can be conveniently used with the ITS P2000 ERT instrument, but also the practical limit of electrode size in a circumferential ring in a 1.5” diameter pipe. Although ERT data from the both sections were collected during the experiments, only the ERT data from the test pipe section would be presented and analysed in this paper.

The transparent nature of the test pipe section allows the progress of each cleaning process to be followed through continuous eye observations (visual inspection). Visual inspection time count and ERT data collection both started when water started to flush through the test pipe section. Visual inspection time count stopped when the section had been visually declared to be fully cleaned, i.e., the last residue of shampoo in the whole test pipe section was seen being gradually thinned down to a spot of sub-millimetre magnitude, and finally disappeared completely. This was also deemed to be the visual cleaning ending point. The ERT data collection would continue for at least 30 s after the visual inspection time count stopped. This was to make sure the collected ERT data captured the full length of the cleaning process.

Fig. 5 shows photos of the pipe geometries being investigated and the ERT electrode planes. The wetted surfaces of each geometry were made from a moulding of the corresponding standard stainless steel part, therefore, are faithful to the real geometry. The geometries include:

(a) Dead-end 1.5” T piece – the geometry is intended to mimic an instrumentation port or a difficult-to-clean section where ‘soil’ could build up. It contains one single ERT electrode plane, situated in the circumference of the dead end pipework.

(b) 2.5” expansion – the middle section of this geometry consists of 22 mm long 2.5” nominal straight section, with a conical entry and exit at the either end so the geometry can be connected to the other 1.5” pipe fittings in the flow circuit. Four electrode planes are fitted on the circumference of the straight section at an equal inter-plane interval.

(c) 1.5” 90° bend – there are three electrode planes, one at the inlet and one at the outlet of the bend, and the third one sits mid-way between the two. The neighbouring pairs are thus at 45° to each other. For this geometry, two configurations were investigated, one with the bend lying horizontal and the other with the bend sitting upright (vertical).
Fig. 4 – A piping and instrumentation diagram (P&ID) of the experimental setup.

Fig. 5 – Digital photos showing the pipe geometries being investigated and the fitted ERT electrode planes (a) 1.5” dead-end T; (b) 2.5” expansion; (c) 1.5” 90° bend; (d) 1.5” butterfly valve.

(d) 1.5” butterfly valve – this is mainly a 1.5” straight section, but with a disc in the middle to mimic a 1.5” butterfly valve in a fully open position. The geometry is equipped with four electrode planes, two at the upstream and two at the downstream of the disc. Two inner planes are at the immediate upstream and downstream of the disc respectively.

Fig. 6 shows a digital photo of the experimental flow circuit involving the 90° bend testing geometry sitting vertical. Table 1 summarises the experimental conditions for each geometry.

4. Results and discussions

4.1. Visual inspections

The purpose of taking the visual inspection simultaneously as the ERT data were collected in the experiment was to benchmark the cleaning progress and provide an independent verification to the ending point of the cleaning process. Among all the geometries investigated, visual inspections revealed that a clear ranking exists in the degree of cleaning difficulties, which can be expressed in a descending order: 1.5” dead-end T > 2.5” expansion > 1.5” 90° bend > 1.5” butterfly valve.

However, not all the ending points were explicitly detectable through visual inspections. This was especially the case with the 1.5” 90° bend and 1.5” butterfly valve. The CIP processes for these two geometries were relatively fast and swift, and visual sightings were impaired by the presence of the electrodes. The visually determined ending points, therefore, could have been severely over-estimated.

The visual inspections also identified a few most difficult to clean spots or regions on different geometries investigated. For the 1.5” dead-end T, looking over the top with the main stream flowing from left to right, the left hand side half of the dead-end pipe, especially the areas along the wall, was seen to be the most difficult to clean region, irrespective of the CIP water flow rate. For the 2.5” expansion, this region lay between the fourth electrode plane and entry to conical exit. In most cases, the last fragment of shampoo was seen being flushed off the surface at the entry to the conical exit. This is some distance downstream of the last electrode plane, which suggests that the visually observed cleaning ending points for this geometry would be longer than the ERT detected ones.
Table 1 – Summary of experimental conditions for each geometry.

<table>
<thead>
<tr>
<th>Test geometry</th>
<th>Number of electrode planes</th>
<th>ERT frame rate (frames/s)</th>
<th>CIP water flowrate (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5° dead-end T</td>
<td>1</td>
<td>0.5</td>
<td>4100, 5400, and 8000a</td>
</tr>
<tr>
<td>2.5° expansion</td>
<td>4</td>
<td>1.0</td>
<td>4100, 5400, 6200, and 8000</td>
</tr>
<tr>
<td>90° bend (horizontal)</td>
<td>3</td>
<td>0.5</td>
<td>4100, 5400, and 8000</td>
</tr>
<tr>
<td>90° bend (vertical)</td>
<td>3</td>
<td>0.5</td>
<td>4100, 5400, and 8000</td>
</tr>
<tr>
<td>1.5° butterfly valve</td>
<td>4</td>
<td>1.0</td>
<td>4100, 5400, and 8000</td>
</tr>
</tbody>
</table>

a Experimental runs at CIP water flowrate 8000 kg/h for this geometry were repeated two more times.
b All the experimental runs for this geometry were repeated one more time.

Fig. 7 – Reconstructed tomograms from the four electrode planes on the 2.5° expansion geometry showing different stages of a CIP operation when water was flushing through at 5400 kg/h.

For the 1.5° 90° bend, the inlet of the bend, where the first ERT electrode plane was situated, was consistently seen to be the most difficult to clean region, regardless of the configurations and CIP water flow rates. Visual identification of this region for the 1.5° butterfly valve, however, has not been possible, due to the cleaning process being too fast.

4.2. ERT results and formulation of automated decisions

Fig. 7 illustrates a representative example of the ERT results, which shows the tomograms of the four electrode planes on the 2.5° expansion geometry at different stages of a CIP operation when water was flushing through at 5400 kg/h. At the beginning, the geometry was filled with shampoo with an average conductivity of 30 mS/cm. All tomograms were thus red. Immediately after cleaning started, large chunks of shampoo started to be removed. After 2.5 min of cleaning, the first two electrode planes were fully cleaned. Only small residues of shampoo remained in top right region of the electrode plans 3 and 4. They were gradually thinned down and the electrode planes became fully cleaned after 4.5 min of cleaning. This example demonstrates that the ERT technology is capable of shedding more detailed insights into the CIP process than any other monitoring technologies currently being employed.

However, it is obvious that the tomograms are of limited use for formulation of automated decisions. The latter requires a universal and quantifiable cleaning indicator to be identified, which defines the CIP ending points by the same criteria for different geometries and different water flow rates.

The data collected in the current investigations was inspected to determine a suitable indicator for the completion of cleaning. Fig. 8(a), as an example, illustrates the behaviours of the maximum, mean, and standard deviation of the pixel conductivities in a complete CIP process corresponding to the 1.5° dead-end T with water being flushed through over the top at 5400 kg/h. The three parameters were initially identified as the hopeful indicators. It can be seen that the mean conductivity over the plane falls to a constant value before the cleaning is complete. Moreover, reliable algorithms for identifying cleaning time based on mean conductivity were dependent on knowing the final mean conductivity of the cleaned test section, so could not identify the cleaning end point in real time. Attempts to identify cleaning based on the distribution of the conductivity over a plane, i.e., standard deviation, could not identify a rule that worked consistently over the whole data set. It was found that the maximum pixel conductivity, $\sigma_{\text{max}}$, which is defined as the maximum of the reconstructed 316 pixel conductivities for each frame, could be the best choice for an indicator that worked over the whole data set without prior knowledge of the final condition:

$$\sigma_{\text{max}}(x) = \max(\sigma_{\text{u}}), \quad w = 1, 2, \ldots, 316, \quad \text{for frame } i$$

Fig. 8(b) illustrates the typical behaviour of this parameter as the CIP process in the 1.5° dead-end T approached complete, with water being flushed through over the top at 4100, 5400, and 8000 kg/h respectively. We can see that as the cleaning came to close to the ending point, the maximum pixel conductivity featured an initial sharp drop to approximately the conductivity value of the cleaning agent (i.e., tap water, $\sim 0.1 \text{mS/cm}$), and then levelled off once the cleaning ending point was reached. These profile characteristics have been consistent regardless of the CIP water flow rates over the 1.5° dead-end T, and were also observed for all the other geometries investigated, although the characteristics in some of the data were more distinctive than the others.

With the maximum pixel conductivity being identified as a reliable universal cleaning indicator, and its behaviours being examined over different process conditions, key criteria were then established to enable the formulation of automated decisions. For the current investigation, a cleaning process would be considered to be completed if:

- the maximum pixel conductivity falls below a threshold of 0.135 mS/cm, and
- the rate of the maximum pixel conductivity variation against two consecutive frames falls below a threshold of $10^{-4}$ mS/cm frame.
Fig. 8 – Behaviours of (a) the maximum, mean, and standard deviation of the pixel conductivities in a complete CIP process in the 1.5° dead-end T with water being flushed through over the top at 5400 kg/h; (b) the maximum pixel conductivity as the CIP process approached end point in the 1.5° dead-end T, with water being flushed through over the top at 4100, 5400, and 8000 kg/h respectively. The maximum pixel conductivity featured consistently a sharp drop to approximately the conductivity value of the cleaning agent when the CIP approached completion.

![Graph showing cleaning starting point and visual cleaning ending point.](image)

**Fig. 9** – Comparison of the visual cleaning time and measured cleaning time for all the pipe geometries and CIP water flow rates investigated.

Furthermore, a moving average approach was adopted, with the maximum pixel conductivity at frame i to be taken as the average of the 7 trailing frame values:

$$\sigma_{\text{max},i} = \frac{\sum_{j=1}^{7} \sigma_{\text{max},j}}{7}$$  \hspace{1cm} (11)

Such an approach could smooth out the noises, and make the criteria applicable to highly noisy data such as the ones observed at the CIP water flow rate of 4100 kg/h in the 1.5° dead-end T (Fig. 8). It is worth pointing out that the above approach is proposed for the specific 16 electrode layout and frame rate used in this study. If more electrodes, or a finer discretisation scheme, were used, the appropriate threshold maximum might be expected to increase. Also, the conductivity variation should be adjusted inversely for changes in frame rate.

### 4.3. Comparison of visual cleaning time and measured cleaning time

A Matlab programme was constructed to implement the automated decisions to all the experimental data collected. **Fig. 9** compares the visually determined ending point time (indicated as visual cleaning time) with the Matlab programme determined ending point time (indicated as measured cleaning time) for all the pipe geometries and CIP water flow rates investigated. It can be seen that:

(i) The measured time produced the same ranking order as the visual inspection did in terms of the degree of cleaning difficulties for all the different geometries, i.e., 1.5° dead-end T > 2.5° expansion > 1.5° 90° bend > 1.5° butterfly valve.

(ii) Results on the 1.5° dead-end T saw the best match between the measured cleaning time and visual cleaning time. This geometry allowed the cleaning end point to be most clearly and confidently verified by the visual inspections.

(iii) For the 2.5° expansion geometry, all the measured cleaning times were shorter than the visual cleaning ones. This is also expected, as the visual inspection revealed that the most difficult to clean region for this geometry lay at the entry to the conical exit–some distance downstream of the ERT sensing domains.

(iv) For the 1.5° 90° bend and 1.5° butterfly valve, relatively large discrepancies were observed between the measured cleaning times and the visual cleaning times in all the CIP water flow rates investigated. This could be attributed to the fact that the accuracies of the visual cleaning time for these two geometries were subject to significant overestimations, as the CIP processes for these two geometries were relatively fast and swift.

**Fig. 10** illustrates the variations of the measured cleaning time as a function of the CIP water flowrate for different geometries. A number of researchers have shown that the cleaning time (tc) or soil removal rate is a complex function of CIP fluid velocity or local wall shear stress (Cole et al., 2010; Lelievre et al., 2002; Jensen and Friis, 2004). For turbulent flows, the wall shear stress, \( \tau_w \), can be estimated by the following empirical relation:

$$\tau_w = \frac{1}{2} \rho u^2$$  \hspace{1cm} (12)
Fig. 10 – Variations of the measured cleaning time as a function of the CIP water flow rate for different geometries.

$$C_f = \frac{0.079}{R_e^{0.25}}$$

where \( \rho \) and \( u \) denote the cleaning agent (i.e., water in the current case) density and velocity respectively, and \( C_f \) stands for the Fanning friction factor, expressed in the Blasius equation. \( R_e \) is the Reynolds number of the cleaning agent in the pipeline. Cole et al. (2010) in particular, observed that in straight pipelines the cleaning time scales with the local wall shear stress via a power law relationship.

This has also been the case for our investigation. It can be seen from Fig. 10 through the regressive data analysis that for all the other geometries except the 1.5° dead-end T, the measured cleaning time, \( t_c \) also follows a power law relationship with the wall shear stress:

$$t_c = 189.56 \rho^{0.834}$$

It is worth pointing out that for the 1.5° dead-end T, cleaning actually took place in a port relatively isolated from the main cleaning stream. In this case the calculated \( \rho \) using the Reynold number and CIP water velocity in the main stream pipeline did not represent the actual magnitude of the 'local wall shear stress'. Hence the data from this geometry seem to have formed a separate group in Fig. 10.

Figs. 11–13 show the bar charts of the measured cleaning times at different ERT electrode planes against the CIP water flow rates for the remaining three geometries investigated respectively. It can be seen that for all the geometries, the cleaning time decreases as the CIP water flow rate increases. Apart from that, there are clear patterns of cleaning sequences that can be established for the geometries having multiple ERT electrode planes. For the 2.5° expansion, for example, the sequence of cleaning is in the same order as the electrode plane arrangement, i.e., the electrode plane 1 is the easiest to clean, and the electrode plane 4 is the hardest to clean. For the 90° bend, the sequence of cleaning is in the reversed order as the electrode plane arrangement, i.e., electrode plane 3 is the easiest to clean, and the electrode plane 1 is the most difficult to clean, regardless of the orientation of the geometry. These results also agree fully with those from the visual observations.

It is worth pointing out also that the flow speed inside all those geometries ranged from 0.4 to 2.4 m/s. The flow time between the electrode planes thus would be much less than 1 second, so the differences in the measured cleaning time were genuine.

For the 1.5° butterfly valve, the measured time (Fig. 13) indicates that the electrode plane 3 has had the longest cleaning time. It points to an area immediately behind the fully opened valve disc being the most difficult to clean region for the 1.5 butterfly valve geometry. The result agrees well with the published CFD simulation results (Toro, 2012), which showed that
static flow regions exist immediately after the leading edge of a butterfly valve disc, regardless of the valve degree openings.

4.4. Testing the robustness of the criteria

The robustness of the criteria, on which the automated decisions were based, was examined first by changing the maximum pixel conductivity threshold from 0.135 mS/cm to 0.125 mS/cm and 0.145 mS/cm respectively, and observing how sensitive the measured times would be to the changes.

It has been found that out of the 77 sets of data, lowering the maximum pixel conductivity threshold from 0.135 mS/cm to 0.125 mS/cm resulted in a negligible change (0.3%) to only one of the measured cleaning time sets. Raising the maximum pixel conductivity threshold from 0.135 mS/cm to 0.145 mS/cm, on the other hand, has led to changes for two of the measured cleaning time sets. The measured cleaning time for the 1.5” dead-end T at the CIP water flowrates of 4100 kg/h was changed from 983 s to 886 s, representing a 9.9% change, and one of the measured cleaning times at the water flowrate of 8000 kg/h for the same geometry was changed from 278 s to 231 s, representing a 16.9% change. Overall, however, it can be seen that the measured time set is relatively immune to the variations of the maximum pixel conductivity threshold, which proves the robustness of the criteria.

The robustness of the criteria was also examined by applying the same criteria to a separate set of ERT data collected using the alternative ITS-V5R instrument system on the 1.5” dead-end T at the CIP water flowrate of 4100, 5400, 6200 and 8000 kg/h respectively. The V5R operates on a voltage-voltage instead of current-voltage measurement technique. This gives an added advantage of delivering considerably improved accuracy across a wider conductivity range. Consequently, the reconstructed conductivity data would appear more noisier as a result of the improved sensitivity.

Fig. 14 summarises the results when the criteria was applied to the ITS-P2000 and ITS-V5R data. It can be seen that despite the two instruments operating on different measurement techniques, the agreement between the measured cleaning time and visual cleaning time for both data sets has been consistent. The agreement on the cleaning time between the two instruments has also been good especially for higher CIP water flowrates of 5400 and 8000 kg/h respectively.

5. Conclusions

This investigation clearly demonstrates that ERT can be a highly effective in situ and real time tool for monitoring water based CIP processes. In comparison with all the other monitoring techniques that have been tested or implemented, the technology is capable of providing much more in-depth information to a specific cleaning process, and subsequently leading to valuable insights into process design, monitoring, and optimisations.

The maximum pixel conductivity, a parameter that can be readily extracted from the ERT measurement data, has been proved to be a sound and robust shampoo cleaning performance indicator. The subsequently formulated algorithm will enable automated decisions to be made to accurately locate the ending time of a specific cleaning operation, and identify both the geometry of worst fouling in a specific cleaning line and the site of worst fouling in a specific geometry.

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