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Development of an electrical tomographic system for operation in a remote, acidic and radioactive environment

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Abstract

The thermal oxide reprocessing plant (THORP) at Sellafield, Cumbria, UK, reprocesses fuel for nuclear power plants. It includes continuous stirred tanks into which reactants are added to produce a heavy metal precipitate. Stirring of the reaction vessel must be continuous and of the right intensity to ensure the precipitation process proceeds as intended. The tanks are operated with a deep vortex, the presence and depth of which provides valuable information on the performance of the precipitation.

Access to the tanks is restricted and visual inspection is difficult due to the opaque nature of the tanks' contents and the presence of a heating jacket. Therefore, a remote method of measuring the vortex depth has been developed based on electrical resistance tomography. The sensor, which is in contact with the tank contents, has been designed to withstand the extreme combined conditions of high chemical reactivity, radiation and abrasion caused by the strongly acidic circulating flow. A data acquisition system (DAS) has been designed to cope with the demanding conditions caused by the high conductivity liquor and the constraint of a long cable between the DAS and the sensor.

A software user interface has been developed which displays the current vortex image and a historical trend of vortex depth. Images of the vortex are obtained using an image reconstruction algorithm based on linear back projection and further processing of these images provides the measurement of vortex depth. Low and high level thresholds can be set to trigger alarm conditions.

Keywords: Electrical; Tomography; Nuclear; Fuel; Reprocessing

1. Introduction

The process under investigation is contained within a glass vessel with two overhead feeds and an overflow at the side. One feed contains a metal salt in nitric acid and the other contains an organic acid. The contents of the vessel (from the two feeds) are mixed to react using a rotating magnetic stirrer bar at the base of the vessel. The reaction products leave the vessel through the overflow at the side. The effect of the magnetic stirrer bar is to swirl the fluids and create a vortex at the centre of the vessel. The size and shape of the vortex depend upon the rotational speed of the stirrer bar. The typical nitric acid concentration throughout the vessel during operation is 3.5 M.

Access to the vessels is restricted and visual inspection is difficult due to the opaque nature of the tanks contents and the presence of a heating jacket. The current form of monitoring the vessel is by means of a conductivity probe located in the central air space caused by the vortex. Under normal operation, the conductivity probe would not be in contact with the process liquor. If the vortex fails, the liquid levels rises until it reaches the level of the overflow and the liquors make contact with the conductivity probe and an alarm is signalled. This is presently unpredictable and gives false alarms, due to splashing of liquor onto the conductivity probe. In addition, very little can be deduced about the internal flow structure within the precipitator vessel (such as size and shape of the vortex).

2. Electrical resistance tomography

The majority of process applications of electrical resistance tomography (ERT) have utilised one or more planes of circular geometry sensors. The information obtained has proven to be valuable and has attracted significant academic and industrial interest as a research and development tool. However, this

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degree of information is likely to be superfluous in an operations environment. In addition, the practicability of fitting an industrial reactor with this type of sensor is likely to preclude this as an option.

Industrial tomography systems (ITS) have developed a linear ERT sensor which delivers the spatial information that is the main benefit of tomographic measurement techniques whilst being suitable for installation in industrial reactors. This type of sensor geometry was well established in the field of geosciences for the detection of sub-surface rock strata through to the detection of archaeological remains such as building, walls and footpaths, identifying both approximate position and size properties. In the geosciences field, it is common to take measurements between two or more linear sensors [1]. With a two-sensor arrangement, it is common for current to be injected between electrode pairs on one sensor, and the potential difference to be measured on electrode pairs on the other sensor. An ERT sensor with electrodes configured in a single linear probe was applied for imaging sub-seabed sediment porosity [2]. The linear ERT sensor was further developed by ITS for measurements of homogeneity and phase interface in stirred mixing processes [3].

The equivalent of the adjacent electrode pair measurement strategy [4] for circular sensors is applied. However, it should be noted that the first current injection is made over the span of the electrodes (1–16 for a 16 measurement electrode sensor) thereby not satisfying the true criteria of the adjacent electrode pair measurement strategy. The process is then repeated by injecting current between adjacent electrode pairs. Based on the reciprocity law [5] and neglecting the voltage measurements on the electrodes used for current injection, the total number of independent voltage measurements is $N_e(N_e - 3)/2$, where N_e denotes the number of electrodes used in the adjacent measurement strategy.

The raw data for each frame produced by the linear sensor with 16 electrodes consists of 104 V measurements which are used to reconstruct a 2D image by the modified sensitivity back projection (MSBP) image reconstruction algorithm [6]. For the purposes of image reconstruction, the sensing zone is assumed to be a rectangle.

3. Feasibility tests

A replica vessel to those used on the thermal oxide reprocessing plant (THORP) at Sellafield is shown in Fig. 1. This experimental facility is located at the University of Leeds and is shown without and with agitation. Initial experiments were performed on this vessel filled with water, brine and concentrated brine with electrical conductivities of 0.1, 3.8 and 250 mS/cm using a linear ERT sensor [7].

Measurements were taken using a standard ITS P2000 ERT system for a range of agitation rates [8]. The voltages and images for tap water are shown in Fig. 2. The graphs show the 104 individual voltage measurements that form a single measurement frame. In each case, the top plot is the measurement voltages, the middle plot is the reference voltages (taken with the vessel full of liquid in the absence of a vortex) and the lower plot is the relative change between the measurement and reference voltages. The images are reconstructed using a MSBP image reconstruction algorithm and electrical conductivity represented by a colour scale. The linear sensor can be thought of as being located on the left of the image and the image represents an orthogonal slice through the vessel. The sensor has been designed with a 'sensing' depth equal to the radius of the precipitator vessel.

Fig. 1. Precipitator vessel without and with agitation.

It can be seen that the voltage measurements respond to the changing vortex depth caused by the increased agitation. The changing vortex is also reflected in the reconstructed images. The colour scale was chosen with red reflecting the conductivity of the liquid. The colours yellow–green–blue represent reducing conductivity with blue representing the lowest conductivity. At an agitation rate of 200 rpm, the vessel contained a shallow vortex and the image reflects this by showing a slight reduction in conductivity towards the top and right of the rectangular image. Increasing the agitation rate to 300 rpm is reflected by the pixels towards the top and right of the image decreasing in value (becoming a combination of yellow and green). Further increasing the agitation rate to 400 rpm is reflected by the pixels in this region decreasing in value (reflected by the colour blue).

Similar experiments were conducted with mild and concentrated brine to provide an indication of performance at elevated conductivity. This was necessary since the final system would have to operate in 3.5 M nitric acid. The results for mild brine were similar to those reported here for tap water whereas the voltage measurements obtained for concentrated brine were outside the range of the P2000 and as a consequence the reconstructed images did not provide any useful information. However, overall these results were encouraging since it has been demonstrated that a linear ERT sensor could detect the presence and depth of the vortex within the precipitation vessel.

4. System development

The following development was needed to provide a successful ERT system for this application:

- Sensor development—materials of construction needed to withstand the extreme combined conditions of high chemical reactivity, radiation and abrasion;
- Hardware development—the combination of high conductivity process liquor and long cable length between sensor and data acquisition system (DAS) would result in the voltage

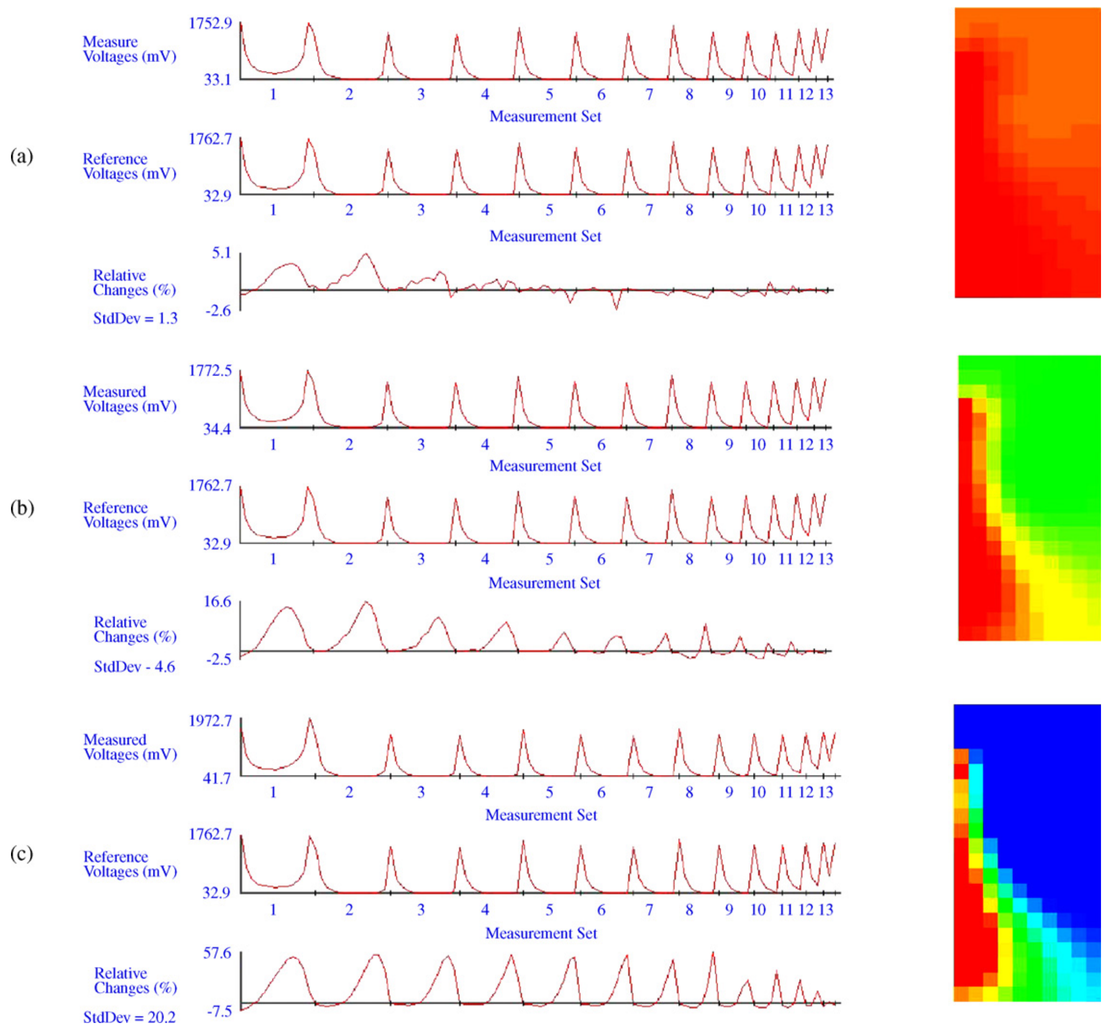

Fig. 2. Voltage measurements and images from vessel filled with tap water at agitation rates of (a) 200 rpm, (b) 300 rpm and (c) 400 rpm.

measurements being small with poor signal-to-noise ratio (SNR);

- Software development—user interface that presented the information in a simple and easy to understand form was required.

4.1. Sensor development

The sensor had to be designed to withstand the extreme combined conditions of high chemical reactivity, radiation and abrasion caused by the strongly acidic circulating flow. The design also needed to ensure minimal disturbance of the flow regime within the precipitator vessel. A photograph of the sensor is shown in Fig. 3. The main body of the sensor was constructed from polyvinylidene fluoride (PVDF) which possesses good chemical resistance, is capable of operating up to temperatures of 150 °C and offers good properties in terms of radiological resistance. The electrodes were manufactured from stainless steel grade 316L, and the design was such that only PVDF and stainless steel were in contact with the process liquor.

4.2. Hardware development

4.2.1. Pre-amplifier

Fig. 4(a) shows the voltage measurements taken from the vessel filled with heated saturated brine ($\sigma = 600$ mS/cm). The scale on the plot of the measurement data varies between −3.5 and 15.8 mV. The measurements less than zero are an indication that these voltages are below the minimum value that the standard P2000 can resolve.

Fig. 4(b) shows data from the same set-up following the addition of a pre-amplifier circuit on the measurement board of the P2000. This improved the measurement resolution of small voltage measurements.

Fig. 3. Linear ERT sensor.

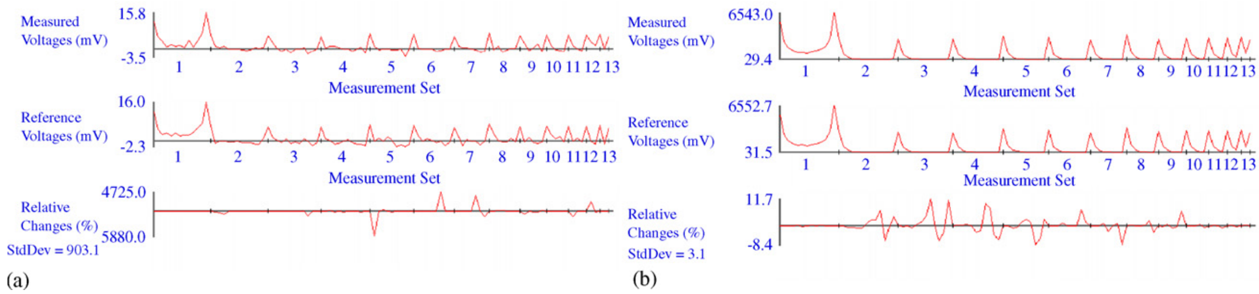

Fig. 4. Voltage measurements collected in concentrated brine (a) without pre-amplifier and (b) with pre-amplifier.

4.2.2. Impedance measurements

Measurements performed with the vessel filled with 3.5 M nitric acid showed that the signal-to-noise ratio (SNR) of the voltage measurements was poor. It is postulated that this may be caused by the electrochemical double layer effect. There is a tendency for charged species to be attracted to or repelled from the metal–solution interface. This gives rise to a separation of charge and the layer of solution with different composition from the bulk solution is known as the electrochemical double layer. This double layer acts like a parallel capacitance to any current flow. The high ionic content of the process liquor was expected to increase the effects of this phenomenon. The hardware was modified to measure impedance with both the real and imaginary components rather than simple resistance. It was also believed that the effect of the electrochemical double layer could be minimised by using a lower frequency and ensuring sufficient interval between individual measurements to allow the double layer to dissipate.

4.2.3. Injection current frequency

Measurements were collected in the absence and presence of a vortex with the vessel full of concentrated brine at injection current frequencies of 1200, 2400, 4800, 9800 and 19,600 Hz. The results indicated that the stability of the voltage signature in the absence of a vortex deteriorated with increasing frequency. The tests at injection current frequencies of 1200 and 2400 Hz failed to discriminate between the absence and presence of a vortex. The best results were obtained with a frequency of 4800 Hz and this value was selected for all future work [9].

4.2.4. Data analysis and software

The ERT system was effective in detecting the presence and depth of the vortex, however, it was necessary to create an output that would give a distinctive 'measurement' of the status of the vortex. The electrical measurements are dependent on, among other things, the conductivity and temperature of the process liquor. Temperature variations to the liquor in the industrial process were expected to be minimal due to the heating jacket fitted to the vessels. However, the ionic strength of the nitric acid was likely to vary over time. Analysis of voltage measurements showed that a small number of the 104 V measurements were less affected by the absence or presence of a vortex (Bennett, 2003). These measurements were used to effectively calibrate the voltage measurements for any changes due to temperature and conductivity of the process liquor.

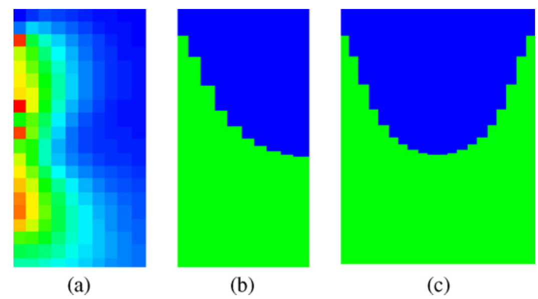

Fig. 5. (a) Raw image, (b) processed image and (c) mirrored processed image.

A method of processing the raw image was implemented to provide a distinctive image of the vortex. The average of the pixel values in each of the 10 columns of imaging pixels is calculated and these are plotted as a bar chart. Due to the presence of the vortex, the average pixel value for each column decreases from left to right across the image. This average value (which is between 0 and 1) can be assumed to be proportional to the volume fraction of liquor and is used to define the interface of the liquor and gas. It is assumed that liquor exists below this point and gas exists above this point. Finally, a mirror image is obtained to produce a representation of the full vortex as shown in Fig. 5.

A software user interface has been developed to acquire the measurements, analyse the data and display the results as shown in Fig. 6. The user interface displays the processed image of the vortex and an historical trace of the vortex depth. Lower and upper thresholds can be defined for the vortex depth and an alarm is registered if the depth reaches either of these values.

5. Final testing

A client acceptance test was performed at the University of Leeds on 21st May 2004. Tests were conducted with the final system as it was to be installed at THORP. The sensor was inserted through the vessel lid close to the vessel wall with the electrodes facing towards the centre of the vessel. Fig. 7 shows the vortex image as the rate of agitation was incrementally increased. It is clear that the vortex image responds to changes in the agitation rate and hence depth of actual vortex. The high and low level alarms were successfully demonstrated.

Following these successful tests at the University of Leeds, BNFL installed a system at THORP. Installation work was performed in autumn 2004, and the system was switched on in November 2004.

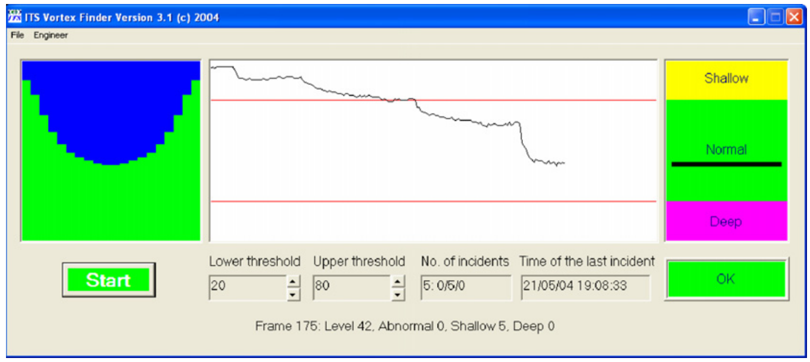

Fig. 6. Software user interface.

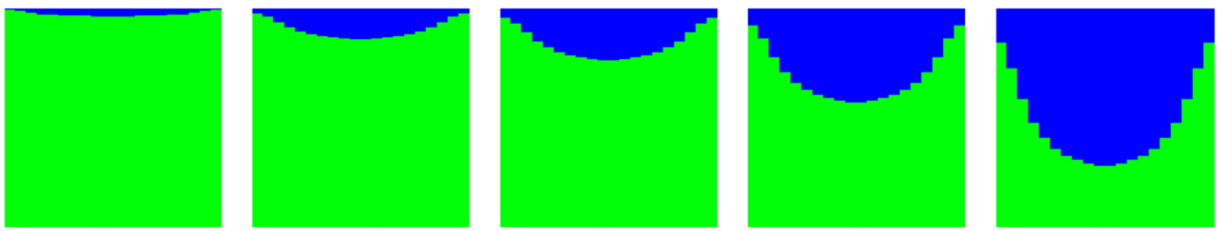

Fig. 7. Process images of vortex at agitation rates (a) 200 rpm, (b) 265 rpm, (c) 320 rpm, (d) 392 rpm and (e) 420 rpm.

6. Conclusions

An ERT system utilising a linear sensor, bespoke hardware and software has been developed to measure the vortex depth in stirred precipitation vessels at THORP, Sellafield, Cumbria, UK.

A number of challenges were overcome. An 18-electrode sensor was fabricated from polyvinylidene fluoride and stainless steel to withstand the extreme combined conditions of high chemical reactivity, radiation and abrasion. A data acquisition system was designed to collect weak electrical signals with poor signal-to-noise ratio caused by the combination of high conductivity liquor within the tanks and the constraint of a long cable between the DAS and the sensor. A software user interface has been developed which has a simple initiation routine, provides the vortex depth in both visual and numerical terms and triggers an alarm condition if the vortex moves outside a pre-defined depth range.

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