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THE USE OF ACOUSTICS FOR REAL-TIME ON-LINE MONITORING OF CERAMIC 'SLIP' IN POTTERY PIPE-LINES

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1 INTRODUCTION

In the production of ceramic ware, for example, tableware or sanitary-ware, the presence of air bubbles in the slip causes faults in the final ceramic articles, which are known as 'pinhole defects' (Figure 1). The defective tableware is rejected, resulting in significant financial losses to ceramic factory, estimated to be 1-2 million Euros per year for a medium size sanitary-ware factory.

These defects arise from the presence of unwanted gas bubbles in the liquid ceramic (called 'slip' or 'slurry'). This is pumped from a settling tank into overhead pipes, from which slip is drawn off through a number of subsidiary pipes before being injected into a mould via a nozzle (in a process not dissimilar to the hand-operated nozzles used in petrol stations for refuelling cars) (Figure 2). The filled moulds are then taken for firing in a kiln, during which process the bubbles expand, creating pinholes which are discovered only after the firing is completed. A persistent source of bubbles can therefore result not only in the loss of many hours of time on the production line, but also in the wastage of slip, since this cannot be recovered from the fired ceramic through recycling.

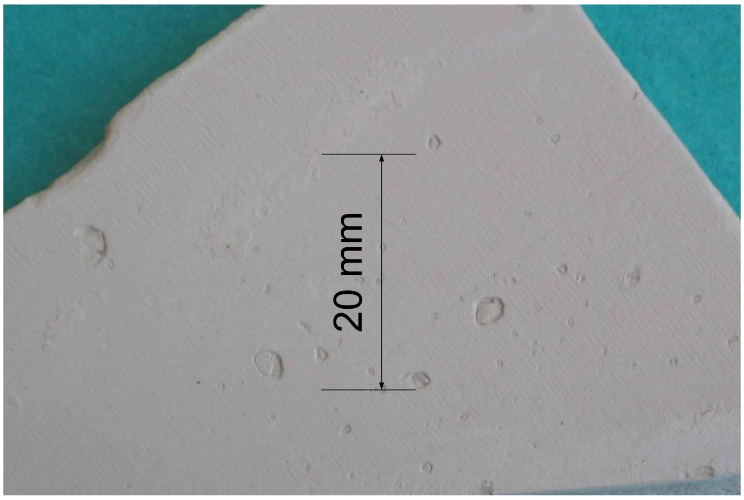

Figure 1. Photograph of a sample of defective ceramic, showing 'pinholes'.

If the air bubbles could be identified and quantified in the slip as it flows through the pipelines before the casting (that is, by continuous on-line monitoring), the slip could be diverted to settling tank or secondary device to eliminate the air bubbles (see white arrow in Figure 2). The object of this research was to provide the prototype for such a device[1].

Such continuous on-line monitoring is not possible using the current state-of-the-art technique employed by the ceramics industry for characterising the content of gas in slip. This technique is known as the 'compressibility test', and it is undertaken only on samples of slip, which represent a very small fraction of the slip flowing at any time. The 'compressibility test' is not on-line and not continuous, and indeed the expertise is not widespread. In this 'compressibility test', the expert removes a sample of slip from the injecting nozzle or the settling tank. A compressive force is then applied to the sample, and the amount by which it compresses indicates the total volume of gas present. Therefore at best this technique provides an estimate of the void faction present (the percentage of bubbly liquid which is made up of free gas). It does not give the bubble size distribution (that is, a histogram of the number of bubbles as a function of the size of these bubbles, with the axis representing bubble size being suitably discretised into size bins)[1].

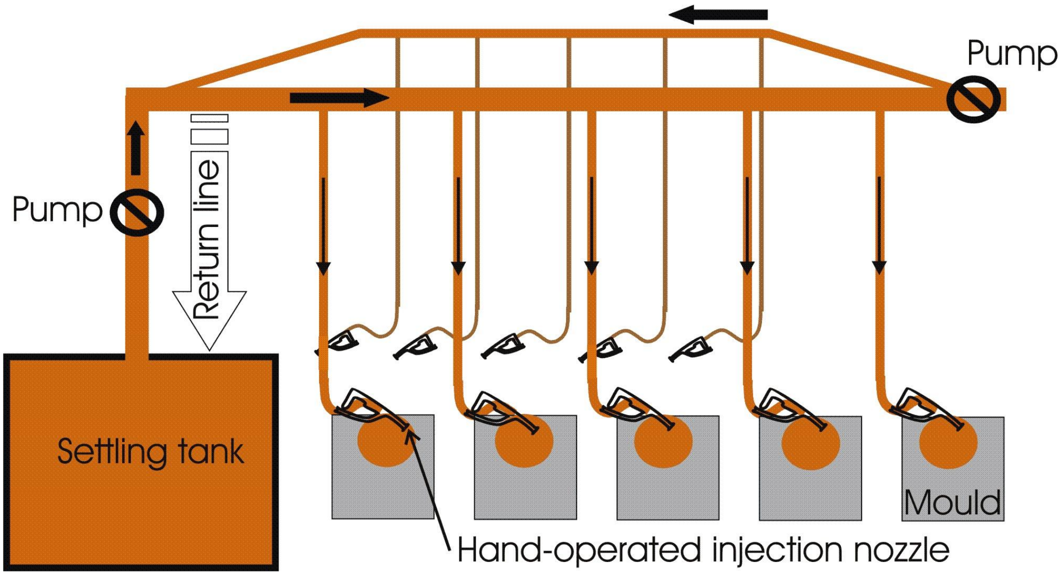

Figure 2. A schematic drawing of a pipeline in a ceramic factory. The white down-facing arrow indicates a possible pumping route, which would return slip to the settling tank if air bubbles were to be detected in the flow.

The disadvantages of the compression method are clear:

- it is an off-line;
- it is performed intermittently (indeed, rarely);
- it makes a measurement on a small sample of the slip, which might not be representative;
- continuous monitoring of air bubble contamination is not possible, and the test certainly does not lend itself to averaging or to monitoring the performance of a factory over time, or in response to changes made to the pipeline;
- it can only be undertaken at the settling tank or nozzle, and therefore cannot be used to ‘track’ back along the pipeline to determine the source of the bubble generations (such as a particular bend or junction in the pipe);
- the operation is slow and entirely manual;
- it requires expertise of a type uncommon in many potteries, both in the execution of the test and in the interpretation of results;
- the test is invasive, and there is the potential for bubbles to be introduced by the measurement process (giving a false positive result) or to escape or dissolve during the measurement (giving a false negative result);
- the sensitivity of the compression test is so limited that even a void fraction which would be considered by factory as ‘high’ (with respect to its ability to ruin the product) is too small to be detected by the compression test (see later).

Therefore, a suitably improved detection device is required for ceramic industry. The desirable features of device are:

- that it should monitor for the presence of bubbles, and determine the amount of void fraction, in various types of slip on line and real-time;
- that the sensors need to be mounted outside of piping (and require no modification to the existing piping), and be able to function robustly despite the wide variations in pipe thickness (both inner and outer diameter) and materials;
- that the whole unit should be designed to be economically viable (i.e. inexpensive, for example, no more than a few thousand Euros per unit) with respect to manufacturing, initial purchase, subsequent operation;
- that the device should be amenable for operation, installation, and the interpretation of results by the unskilled user.

A range of acoustic techniques is available for characterising the bubbles in liquids[1,2]. The choice of which to use depends on the information required, and the availability of funds, equipment and expertise. The medium under consideration is also important, as is the environment in which it is contained (which may range from the oceans[3] to pipes[4,5], environments which each present their own peculiar difficulties). The sound emitted when bubbles are first entrained[6] (by injection to nozzles, or entrapment under breaking waves or waterfalls etc.) can be used to characterise the bubble population so formed, a technique which has been exploited both in terrestrial seas and off-world[1,7,8]. The direct observation of resonance frequency of a bubble allows estimation of the size of a bubble by driving the sound field with a broadband signal (a series of tones with incrementally changing centre frequencies; a chirp; a pseudorandom sequence etc.) which covers the potential bubble resonance[9]. Since the bubble pulsation amplitude peaks at resonance, then monitoring of the attenuation or scattering of a signal at a given frequency has been interpreted as a technique for counting the number of bubbles resonance at that frequency. This method has been popular, but suffers drawbacks, because bubbles close to resonance contribute to the effect (depending on the bubble damping) and, if there are very large bubbles present, these can contribute significantly to the attenuation or scattering. They do this, not because they are pulsating in sympathy with the driving field, but because they simply represent very large targets. Therefore interpretation of the attenuation, scattering, or changing sound speed at a given frequency in terms of only those bubbles which are resonance at that frequency can lead to errors. More sophisticated versions of this acoustic inversion (whereby the measured acoustic propagation parameters are "inverted" to estimate the bubble population which determined them) are available[3].

Because the bubble is inherently nonlinear, there are variations on this technique which exploit the generation of second harmonic and other signals. Other techniques which exploit nonlinearity (or least cyclostationarity)[9,10] are the combination-frequency and modulation-frequency techniques[11,12]. These use very high frequencies, usually of MHz order (such that this frequency is much greater than the pulsation resonance frequency of any bubble present). With such high frequency beams it is possible to produce a time history of the cyclically varying geometrical scattering of the bubbles. In one such implementation, the combination frequency technique involves driving the bubble at its resonance (using the lower frequency ‘pump’ signal) at the same time as the high frequency ‘imaging signal’ is projected into the sample volume. Scattering of the imaging signal allows monitoring of the nonlinear behaviour by examining the harmonics that appear as a result of the modulation of the high frequency carrier signal.

The ideal situation would be to deploy several techniques simultaneously in order to overcome the limits of individual technique[2]. The choice of technique for a given industrial application depends on the information required of the sensor, which is case-specific. An over-sophisticated measurement system is unwanted for ceramic factories. This is because of the complexity and variability of the pipe network and piping material, and because of the different dimensions of pipe section which the device would encounter (if only because the acoustic field will be modified by piping parameters). These variables have implications for the cost, and the requirements placed on the operator expertise, and on the installation procedure for the instrument. A design which is robust for these various deployment options, and which is also inexpensive and user-friendly, is necessarily restricted.

Table 1 summarises the range of size of bubbles, and void fractions in the slip, required of the device. It also indicates the limitations of the sensitivity of the compression method. Note that the sensitivity of the compression test is so limited that even a void fraction which would be considered by factory as ‘high’ (with respect to its ability to ruin the product) is too small to be detected by the compression test. The void fractions in the table are based on compression test.

The table also indicates the resonance frequencies for the bubble sizes listed. These resonance frequencies are lower than the corresponding resonance frequencies for air bubbles of the same size in water, because of the differences in density and viscosity of slip[10].

Parameter	*Magnitude*	*Comment*
Maximum bubble size	1000 µm	Resonant at 2.5 kHz
Minimum bubble size	50 µm	Resonant at 50 kHz
Min. detectable void fraction	0.002%	Using the compression test
A ‘huge’ void fraction	0.03%	Detectable by compression
A ‘large’ void fraction	0.01%	Detectable by compression
A ‘high’ void fraction	0.001%	Not detectable by compression

Table 1. Typical detection range requested by industry

2 METHOD

The acoustic detection of bubbles in the slip is investigated through analysis of the bubble-mediated change in the sound field within the pipe. Bubbles affect the incident sound field by scattering and absorption. As introduced in section 1, the scattering of ultrasound by the bubble has a local maximum at resonance frequency because of its oscillatory behaviour, which can give the bubble size information. To identify the resonant characteristics of bubble, the sound field needs to be insonified with a series of tones, or some other broad band signal, to find the bubble in resonance. This in turn requires a broadband sound source. Such sources are expensive, and a market analysis for the project indicated that incorporation of a broadband source into the design of the device would make the cost of any marketable sensor, developed from our prototype, more expensive than the potteries would be willing to pay.

A cheaper alternative is therefore needed. In section 1, the modulation frequency technique was introduced, whereby the bubble population is diagnosed from the time-varying scatter of an imaging signal from a bubble driven to pulsate by a pump signal. Such technique would be impractical for the ceramics industry, because of the complexity of propagating a MHz imaging signal through various pipe walls and slip, and because the design would be even more complicated (requiring not just a broadband pump transducer but also the imaging transducer). However bubbles of the size indicated in Table 1 offer another option, whereby the modulation of the scattering by a bubble is not the result of its being driven to pulsate by a pump signal, but rather comes by another source.

The cheapest transducer that can be found, which is capable of transmitting through the various pipe walls and slip and still maintain an adequate signal-to-noise ratio, is narrowband, transmitting at a single frequency. Furthermore, this single frequency could not be particularly high, such as is used for biomedical imaging, because of the very high attenuations in slip and pipe. At first sight, this appears to be a very poor option for detecting bubbles in ceramic slip: the millions of ceramic particles in the slip itself will scatter the sound; and the lower frequency will give poor spatial resolution and so not allow imaging of bubbles.

However from these apparent disadvantages, a powerful sensing system can be devised. If the lower frequency ultrasound is projected into the pipe, it will insonify a region having a volume of O(litre). Every second, millions of slip particles will leave this sensing volume, to be replaced by millions more. The statistics of the scatter will not change. However if a bubble enters this volume, the statistics of the scatter will change significantly.

When the bubble is insonified with much higher than its resonance frequency, the bubble-mediate change is still distinguishable. There are many mechanisms which contribute to this distinction. The scattering cross-section of the bubble can change as its shape changes, just as with the modulation techniques described above (which can detect higher orders of shape oscillation than just the pulsation)[10,12]. The contribution made by the bubble to the signal received by the sensor will depend on the amplitude of the sound field at the bubble, which will vary with the bubble's location in the pipe. The bubble will impart phase changes to the scattered signal, again altering the received signal[13]. Its scattering will change because of perturbations in its geometric motion, which in turn depends on the size and shape of the bubble. When the bubbles rise up or move with the fluid flow, the motion and trajectory of bubble are different from those of solid ceramic particles in slip, as it has higher buoyancy and its shape can be deformed, resulting in changes in the wake behind the bubble[14]. The oscillatory or irregular motions of bubbles contribute signals which can allow the ultrasonic systems to distinguish between the bubble and the slip, as both pass through the region of pipe which is insonified, and from which scattering is detected.

The project budget was very restricted, so that the device had to use those transducers which could be obtained gratis. The two transducers (one to be used as the transmitter, and the other to be used as the receiver) were found to be strongly resonant at 32 and 37 kHz. The conductance and reactance of transducers are presented on Figure 3. These results were obtained using an HP impedance analyser (model 16047A). The majority of the acoustic energy that these transducers produced was centred between 32 and 37 kHz, which are much higher than the resonant frequencies of bubbles interested. Therefore, whilst it would be impossible to exploit the bubble resonance in the detector, these transducers possess the characteristics required of an imaging signal.

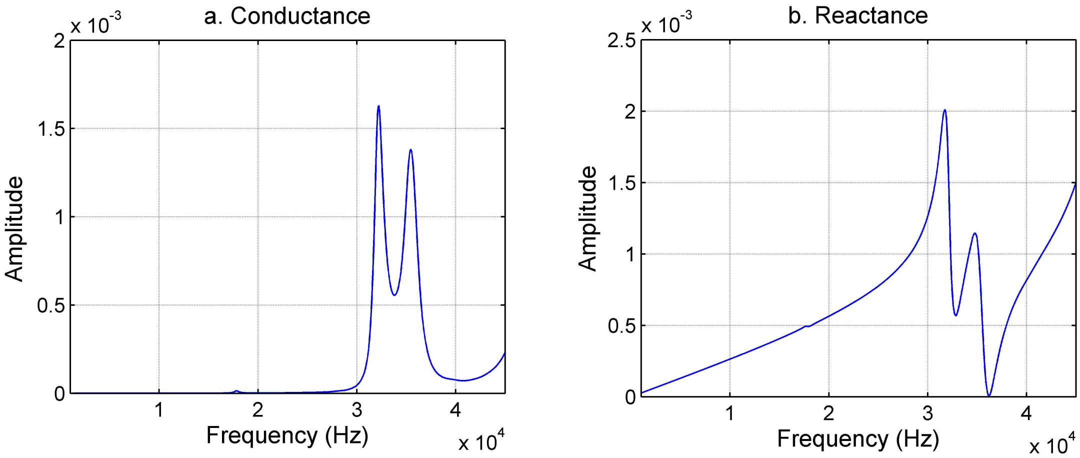

Figure 3. Results from impedance analyser test, showing (a) the conductance and (b) the reactance of transducers, These results were obtained using an HP impedance analyser (model 16047A).

The sound field generated by such transducers of course depends on the environment into which these transducers are introduced. Figure 4 shows the pressure amplitude measured along the centre line of the vertical section of pipe using the B&K 8103 hydrophone. The sound field was insonified with the 37 kHz sinewave using the above transducer mounted outside of pipe. The origin (z=0) is set as the vertical position of the transducer.

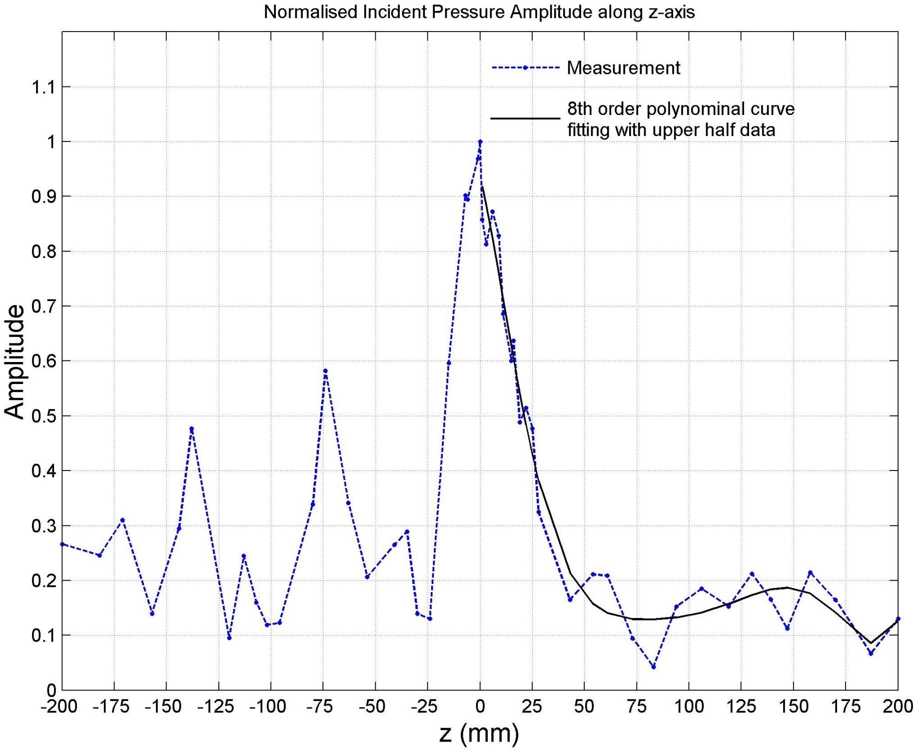

Figure 4. The acoustic pressure amplitude measured along the centre line of the pipe, when the transmitter and receiver contacts are placed on the outside of a section of water-filled pipe. The pipe was made of PMMA having external diameter 64 mm and inner diameter 55 mm, and the length of the water column within it was 1.3 m. The transmitter operated at 37 kHz.

A study was conducted to model the contributions to the received signal of the various mechanisms discussed above. By characterising the magnitudes of these effects, their relative potencies in perturbing the received signal could be determined, and hence those perturbations could be quantitatively interpreted in terms of the bubble population present. This ability to model the separate contributions is particularly important for this, since it is difficult in real experiments to invoke each mechanism separately. This is because, for example, shape oscillations, the inhomogeneous sound field, the wakes and the bubble motion all interact. As such, it cannot automatically be assumed that the separate contributions of each mechanism to the sound field add independently. Nevertheless this is an important exercise in assessing the magnitudes of the contributions.

An example of this study is shown in Figure 5, where reverberation, non-uniform motion, wake effects and shape oscillations have been removed from the study. The only contribution to the perturbation seen in Figure 5 is the simple uniform translation of the bubble through an insonified region (which, since the effects of reverberation – such as are measured in Figure 4 – are removed from the model, is assumed to be free field). Figure 5 shows the amplitude modulation of the received signal by a single bubble which passes vertically up the axis of a vertical pipe, in the sound field of 37 kHz sine wave. Even without the contributions from the other mechanisms, the amplitude modulation which passage of the bubble indices is clear. The passage of the bubble causes the amplitude of the received 37 kHz signal (which in the absence of the bubble retains a constant amplitude at the receiver) to undergo modulation, reflecting the passage of the bubble through the beam.

As a result of such studies, the decision was made to base the prototype on the amplitude modulation of the 37 kHz 'carrier' or 'imaging' signal. The envelope characteristics of the received signal were consequently extracted and plotted as a time history, and the cumulative energy in this related to the void fraction present.

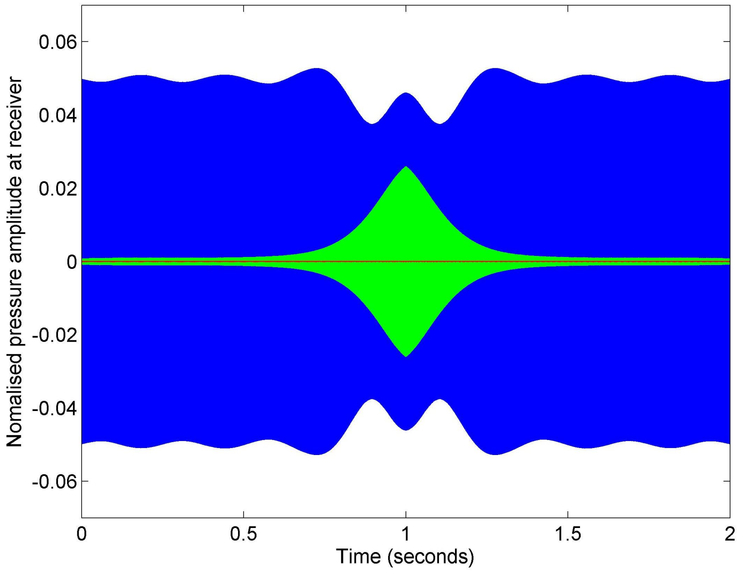

Figure 5. The modelled modulation of the 37 kHz pressure fields at the location of the receiver as a bubble (of 0.75 mm radius) rises vertically up the central axis of the pipe, translating at uniform velocity. At closest approach, the bubble is 2.7 cm distant from the receiver. During the 2 s window over which these data are modelled, the bubble rises vertically by 32 cm. The 37 kHz sound field is modelled as being that which would be generated by the transmitter in the free field. The 37 kHz sine waves plot so densely that they appear to provide solid blocks of colour, such that only the amplitude modulation of this signal is visible. Whilst the pressure scattered by a single rigid sphere having the same radius as the bubble is insignificant on this scale (red curve), the pressure scattered by the bubble is much larger (green curve). This causes significant modulation in the amplitude of the signal at the receiver (blue curve).

3 RESULTS

To develop and characterise the prototype before its testing the factory environments, a scaled version of a factory rig was built in the laboratory at ISVR. The rig consists circulating piping, slip reservoir, diaphragm pump and supporting structure. One of the vertical pipe sections was chosen for 'static' or 'flowing/pumped' tests (i.e. when the pump was, respectively, not activated, or activated). The rig could be filled with water or slip (although the latter could only be used in flowing (pumped) tests or else it would set). The inner diameter of the pipe was 55 mm and the wall thickness was 4.5 mm. The sensor was mounted on a vertical section of pipe. Air bubbles could be introduced through a hypodermic needle, inserted through the wall of this vertical section, below the level of the sensor. When water was used, the size of bubble could be estimated by optical observations (including photography) and cross-checked with the size calculated from the measured rise speed of bubble[15].

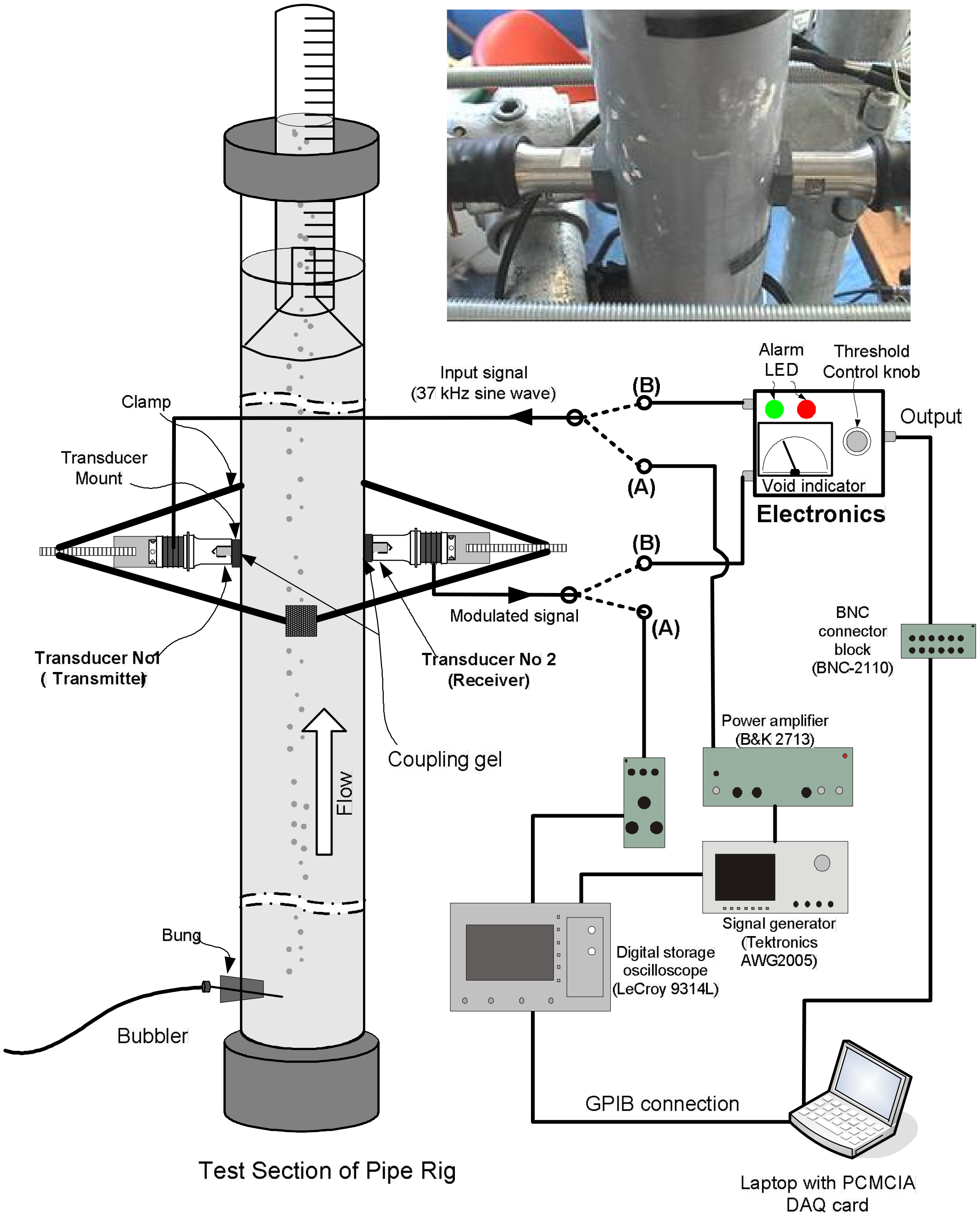

Figure 6. Schematic (with photographic inset) of laboratory experiments with water filled 'static' pipe rig. The rig could also be filled with slip and closed to form a pumping loop resembling that shown in Figure 2.

Figure 6 shows the layout of the experimental rig, when it was water-filled and configured for 'static' tests. This useful configuration was obtained when the flow loop was opened above a vertical section of pipe (the so-called 'static' rig since flow could not be pumped through it, as it was no longer a closed system). When used in ‘static’ mode, with the vertical pipe was opened above the sensor, the height from the bubbler to the free surface was 1.85 m. This allowed the void measurement to be undertaken simultaneously with the acoustic measurement. Using the measuring cylinder and flask, the air bubbles were collected at top of the test section and void fraction was calculated. It is this arrangement which is drawn in Figure 6.

The inset photograph (at the top right of the Figure) shows the transmitter and receiver transducers mounted on the middle of test pipe when it is filled with ceramic slip. To enhance the impedance match with the pipe[13], uPVC adaptors matching the outer curvature of pipe were inserted between transducer head and surface of pipe. These are visible in the photograph. Coupling gel was applied to these surfaces. In the initial experiments whilst the prototype was developed and refined, standard laboratory equipment (shown in Figure 6, arrangement (A)) was used. Initially the 37 kHz sinusoid was generated using the signal generator (AWG2005 arbitrary waveform generator) and transmitted to the transducer via power amplifier (B&K T2713). The output signal from receiver transducer was conditioned by preamplifier (B&K T2635) and displayed simultaneously with the input signal on the oscilloscope (LeCroy 9314L). The data was sampled at 200 kHz and saved to a PC via GPIB connection. A Matlab program was used to control the equipments, data acquisition and analysis of data.

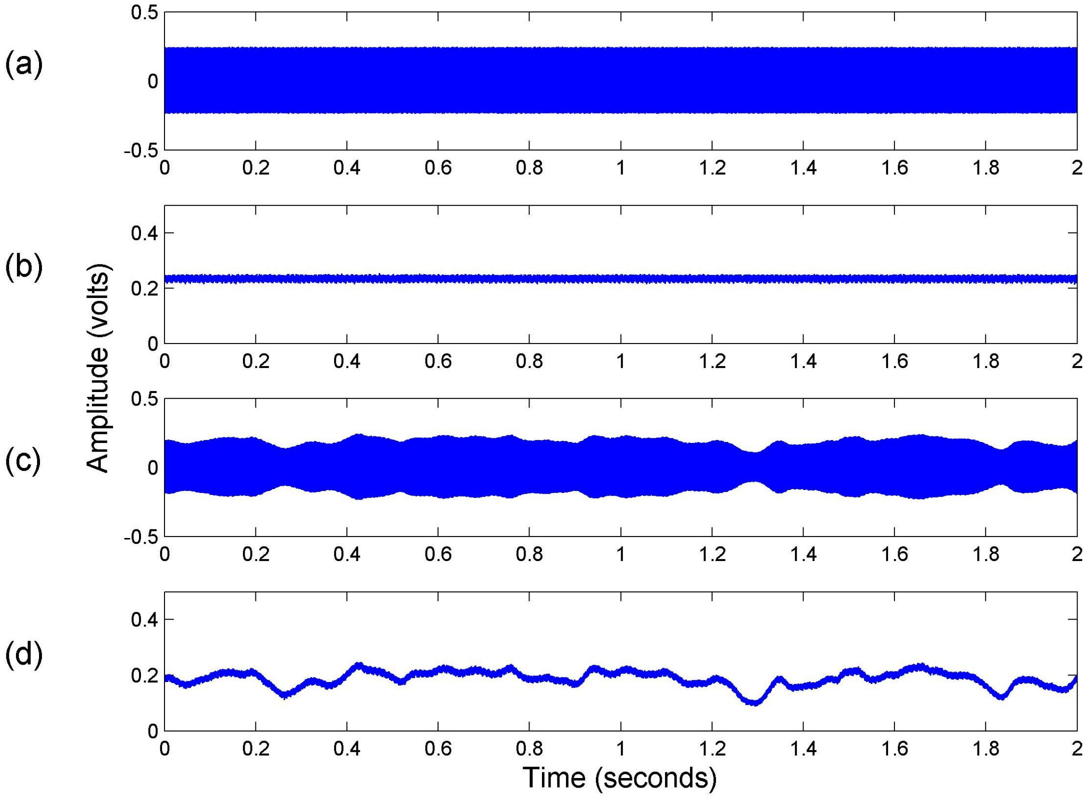

Figure 7. Comparison of detected signals on a common time axis, with and without bubbles present, and both before and after processing for envelope features. (a) The raw 37 kHz signal from the receiver, when no bubbles are present. (b) The envelope calculated from the signal of part ‘a’. (c) The raw 37 kHz signal from the receiver, when bubbles are present. (d) The envelope calculated from the signal of part ‘c’.

Since inclusion of such items in the final prototype would make it prohibitively expensive according to the market survey undertaken, the development of the prototype entailed their replacement with a compact electronics unit (shown in Figure 6, arrangement (B)), which was used for the factory trials.

Not only does this unit generate the transmitted signal, and acquire the output of the ultrasonic receiver, but it also undertakes the processing and indicates, through the use of a ‘traffic light’ system, whether the device considers that the level of bubbles detected in the flow warrants cessation of mould filling and return of the slip to the settling tank (as indicated by the red light shown in Figure 6) or not (as indicated by the green light shown in Figure 6).

The received time signal, with and without bubbles in the water in the pipe, is shown in Figure 7 (the water was not being pumped for this data, so that Figure 7 represents a ‘static rig’ test). In the no-bubble mediated condition, the carrier frequency is detected without amplitude modulation (Figure 7 (a)). Using the Hilbert transform, the envelope component is separated (Figure 7(b)). When bubbles are introduced into the pipe, the carrier signal begins modulating (Figure 7(c)), and, after processing, its envelope can be plotted as a time history (Figure 7(d)).

The ultrasonic estimation of void fraction was undertaken by using the square of demodulated voltage, which is plotted with measured void fraction on Figure 8. Here the void fraction was measured at the free surface in the open static rig, where the bubbles were collected for void measurement using measuring cylinder and flask.

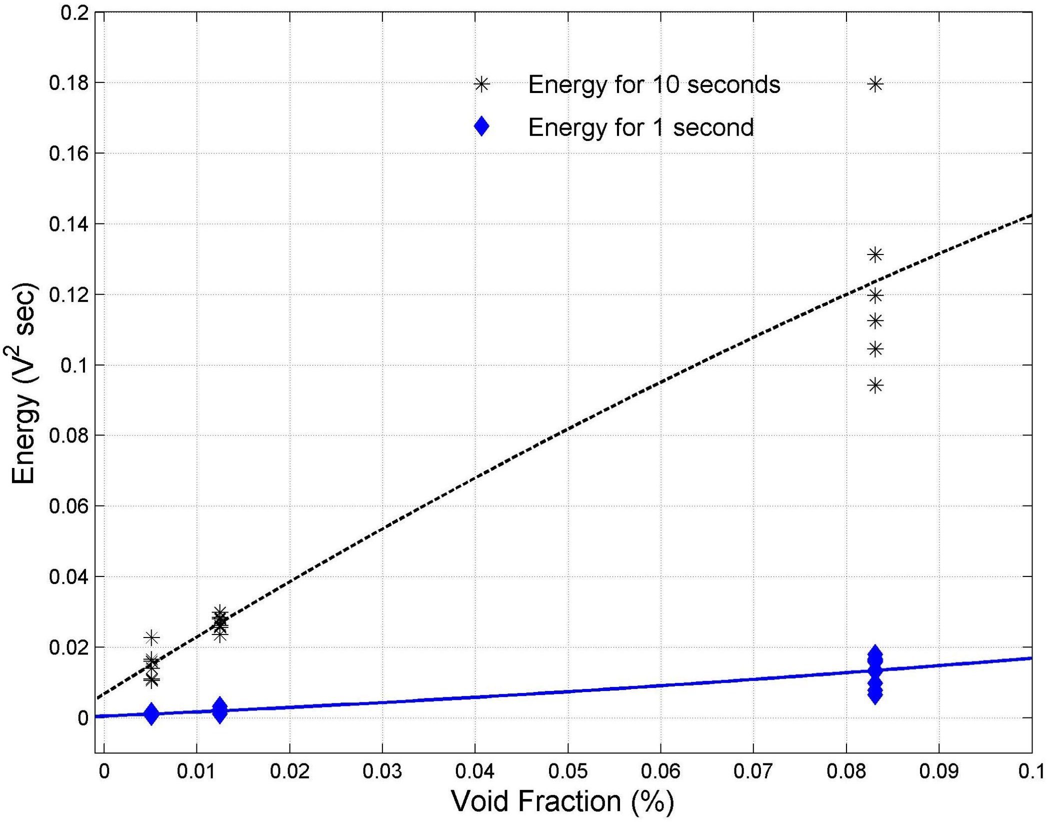

Figure 8. Comparison of the acoustic measurement (the integration of the envelope, such that V^2 sec. provides an energy-like quantity) with the results of void fraction measurement, undertaken in the of water-filled static rig (the void fraction was measured by collecting of rising bubbles using measuring cylinder and flask, and correcting for the variation in rise speed with bubble size). The results are shown for integrations of the acoustic signal for both 1 s and 10 s.

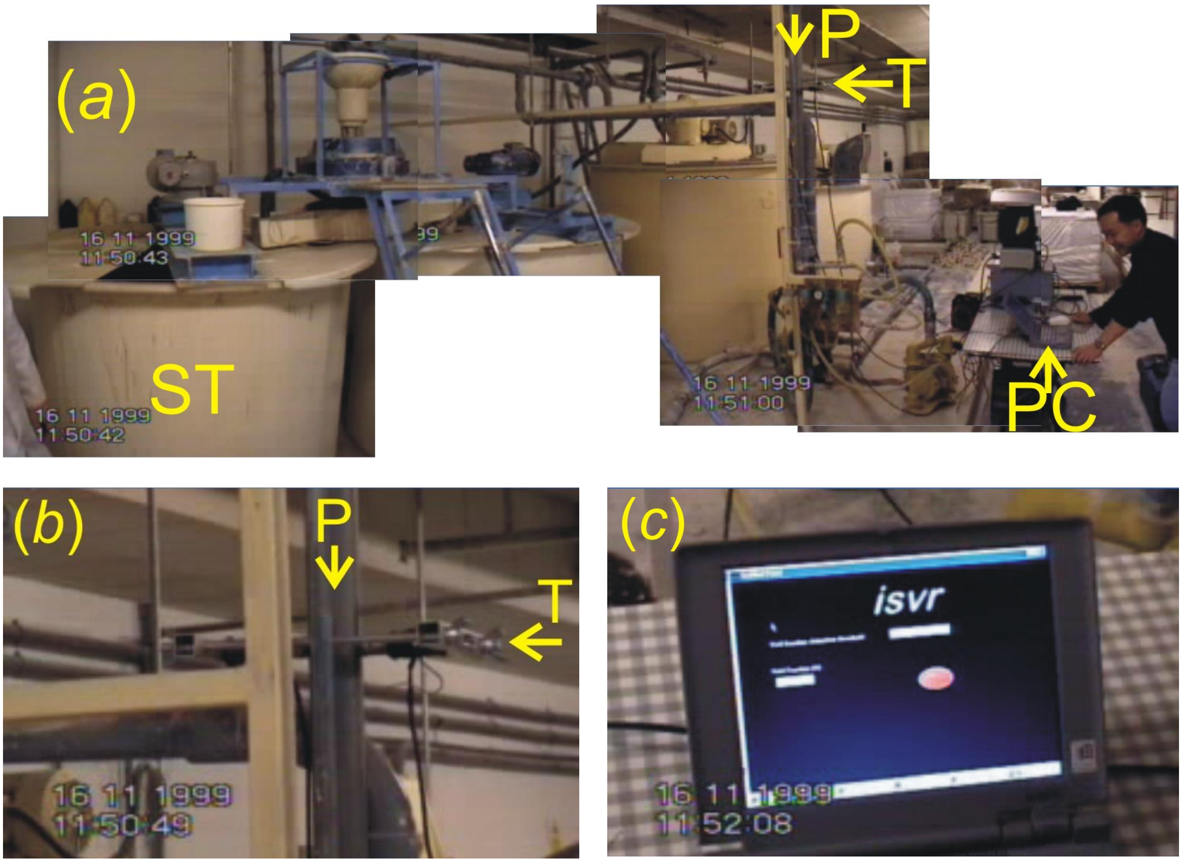

Figure 9. Frame from a video sequence filmed at the Bridgwater Pottery (Stoke-on-Trent, UK) During testing of the prototype (16 November 1999). (a) Slip flows from the settling tank (ST) through the pipelines. The transducers (T) are attached outside of one particular downpipe (P). The output of the receiver transducer is monitored by one of the authors (GTY) on a PC. (b) Detail of the pipe and transducers. (c) The 'light' on the PC has switched from green to red following the addition to bubbles to the flow. The Bridgwater tests were the first in the development of the prototype. In later trials the PC was replaced by a stand-alone unit.

After testing and development on the ISVR test rig, the device was tested in the following factories:

- Bridgwater Pottery (Stoke-on-Trent, UK) (Figure 9);
- Quality Ceramics (Arklow, Ireland);
- Koninklijke Sphinx (Maastricht, Netherlands);
- Porcelanas Bidasoa (Irun, Spain).

Figure 10 shows time history of the output signal from the finished prototype. To make this output, the time history of the envelope is divided into consecutive time bins or windows, typically of duration O(10 ms). Within each time window, the envelope modulation is squared and integrated. This provides, within each time window, a single value which is then plotted against the start-time of that window. Whilst it gives the constant voltage of a little over 1 V for the bubble free medium, bubble mediated changes are clear, giving in this case a time-varying signal (representing the time-varying void fraction) at a higher value, here between 4.5 V and 6 V.

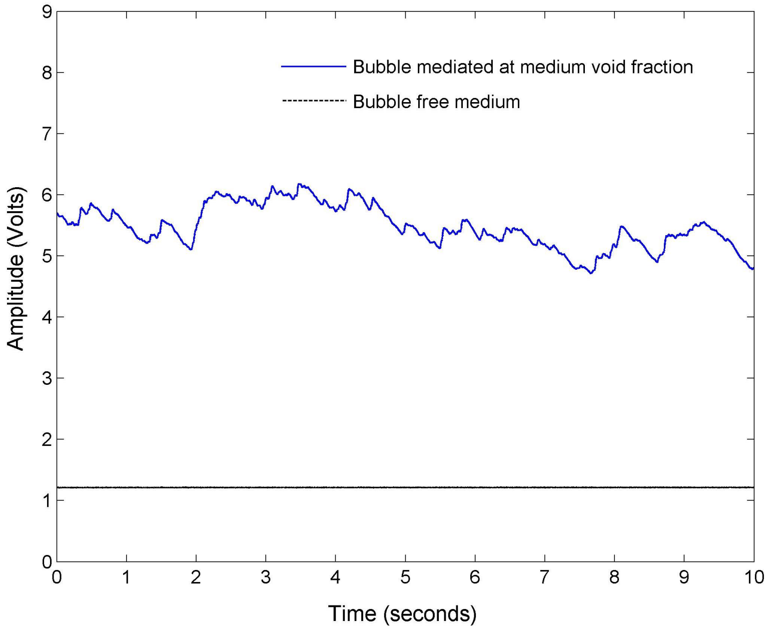

Figure 10. The time history of the output of the prototype electronics.

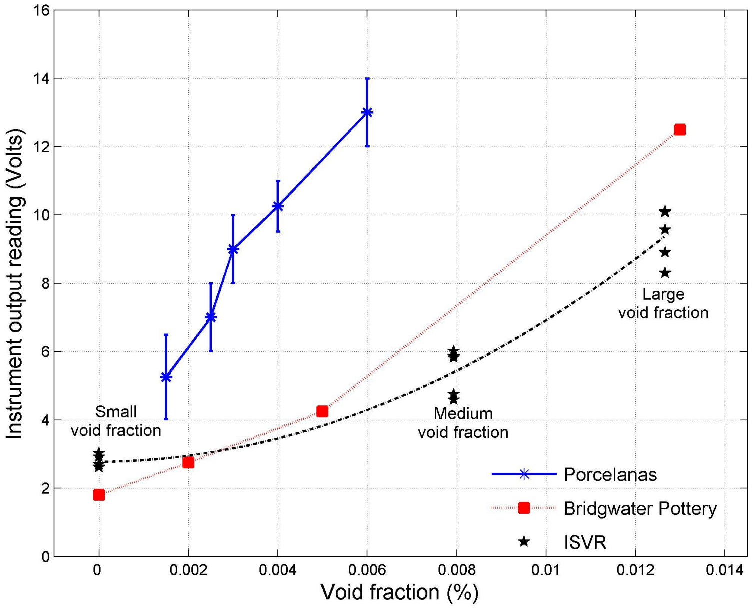

Figure 11. Examples of factory trial results for the measurement of void measurement within pumped ceramic slip during factory operation (at Porcelanas and Bridgwater). The plot shows the calibration curves obtained using the compression test. Also shown are the results obtained within the test rig at ISVR in pumped slip. There are two important differences between the ISVR data and the factory data. First, unlike the factory data, the data in the rig at ISVR were not taken during real factory operational conditions. Second, unlike the factory data, the void fractions against which the ISVR data are plotted were not measured with the compression test, as this was not compatible with the ISVR rig. Therefore it would be inappropriate to compare the void fractions of the factory data on this plot with those against which the ISVR data are plotted. Consequently, the ISVR data points are labelled as having 'small', 'medium' or 'large' void fractions, and no correspondence with the void fractions on the abscissa should be inferred.

4 CONCLUSIONS AND FUTURE WORK

Following laboratory experiments, carried out to detect bubbles in water (in both static and flowing conditions) and ceramic casting slip (flowing conditions only), an inexpensive and compact prototype detection unit was produced for use in practical trials at four ceramic factories around Europe. Whilst the earlier stages of the prototype were PC-based, the later stages progressed onto using a self-contained unit.

The prototype was used in parallel with a compressibility test to detect the level of air contamination in the slip systems studied. The results were well correlated with the compressibility results and were effective on both metal and plastic pipeline systems in factories (Figure 11). The ultrasonic unit proved to be considerably more convenient to operate, and could be used to monitor a moving slip supply continuously, which is not possible using compression techniques. Furthermore it is non-invasive. During the field trials the system proved equally capable of being used in a diagnostic function with respect to the source of the problem, to establish the causes of air bubble contamination, and to monitor a slip supply on a semi-permanent basis, automatically signalling an alarm when excessive amounts of air are present. The physical mechanisms and sources of the envelope modulation on the output signal are under investigation. Completion of this work should reduce the need for an empirical calibration.

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