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An Appraisal of Techniques for the Detection of Interfaces in Continuous Flow Processing Systems

June 1996

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Food Research Association

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CONTENTS

SUMMARY

Two sensing techniques, electrical conductance and ultrasound, were evaluated in terms of their ability to detect liquid-liquid interfaces such as those between water and product on-line under continuous flow conditions. Interfaces between water and a range of products were created, the products being 2%, 4% and 6% w/v Colflo 67 starch solutions, 10% and 50% w/v glucose solutions, full cream and semi-skimmed milk, 2 and 5% v/v caustic solutions, and 0.5 and 1% v/v citric acid solutions. Three flowrates were used: 10, 50 and 110 litres/min. The tests were carried out under ambient temperature conditions with both liquids at the same temperature. Results showed that the ultrasound sensor was more suited to liquid combinations which exhibited a large difference in rheological characteristics. The conductance sensor was generally more suited to the cleaning solutions. These findings were not universally applicable however.

For given combinations of liquids, flowrate was found to have a significant effect; the performance of both sensors improved with increasing flowrate. However, it was found that changes in dilution of the liquids made little change to the signals at a given flowrate. Both sensing techniques showed sufficiently rapid response to be useable on-line.

1. INTRODUCTION

Product changeovers are an essential part of continuous flow food processing operations. For example, UHT processing plant is started and stabilised using water and when the plant is ready the water is replaced by product. Similarly, during clean-in-place (CIP) procedures it will be necessary to change from water to cleaning solutions and back again. For these situations it is clearly necessary to be sure that all of one liquid has been replaced by the second liquid before the next stage of a process can begin. The normal method for ensuring this is to allow a sufficient quantity of the second liquid to flow through the plant and to waste. This waste is of economic significance both in terms of product loss and loss of production time. A method of being able to detect the passage of the liquid-liquid interface through some critical point in the plant would enable the wastage to be reduced to a minimum and thus realise economic benefits.

The replacement of one liquid in a filled pipe with another results in the creation of an interface zone between the liquids. The nature of the interface depends upon the rheological characteristics of the two liquids, the nature of the pipework through which they are flowing, and the flow regime itself. The interface can vary from being a clearly defined boundary between widely dissimilar liquids in a smooth flow regime to a zone of dilution between similar liquids in a more turbulent flow regime. Furthermore, density differences between the liquids will result in layering effects where the less dense liquid will flow over the top of the more dense liquid.

A sensor for detecting and monitoring interfaces must be able to differentiate a wide variety of interfaces. Those outlined above could be considered as extremes. The sensor should be arranged to detect the presence of layering. In addition it should operate on-line and be as unobtrusive in the pipe as possible so as not to create atypical flow conditions which would give rise to false readings or create a hygienic risk.

1.1 Literature Search

The bulk of previous reported work in the area of interface detection has been carried out in static conditions at laboratory scale.

Laycock (1969) described an acoustic sensor for detecting liquid-liquid interfaces within a vessel. This relied on the reflection of a pulse of sound from the interface. For this technique to be successful it was necessary for the interface to be a clearly defined boundary and for the two liquids to have differing acoustic properties. The approach described would be unworkable in a continuous flow system.

Chan *et al.* (1993) described a technique using light reflection to determine the shape of liquid-liquid interfaces in a static vessel. Again, this would be unworkable in a continuous flow system, particularly with opaque liquids.

A more suitable system was described by Hoyt (1979) in which ultrasound was transmitted across a pipe in which liquids were flowing. Provided that the velocity of sound in the two liquids differed sufficiently, the interface could be detected by the change in time of flight of the ultrasound signal across the pipe. The sensing technique was described in relation to the petro-chemical industry.

Bozicevic (1979) described a technique using the electrical properties of the liquids to detect the passage of a liquid-liquid interface along a pipe. The technique measured resistive and capacitative properties, depending on the nature of the liquid, within a sensing area built into the pipe.

A survey of commercially available sensors used for on-line monitoring in continuous flow processing plant revealed that ultrasound is used for monitoring physical parameters such as density, particularly in the brewing industry. This suggests that it could be used for interface monitoring. Electrical conductance sensors were also available. However, there appeared to be no sensors specifically developed for the purpose of interface detection, and no other sensor types that could easily be employed.

For the purposes of this work it was decided to consider two sensing techniques: ultrasound and electrical conductance. Furthermore it was decided to develop prototype sensor systems specifically for the project. This allowed the sensors to be integrated with datalogging hardware and software so as to allow the data from the sensors to be captured and recorded at high frequency.

The objectives were as follows:

* To identify suitable sensing techniques for the on-line detection of liquid-liquid interfaces in continuous flow processing systems.

* To evaluate the sensing techniques for sensitivity to a range of relevant liquid combinations which give rise to interfaces over a range of flowrates.

2. EQUIPMENT AND METHODS

2.1 Flowrig

A flowrig was developed specifically for the trials. It consisted of main and secondary liquid tanks coupled to the pipework via a 3-way valve, a pump, a sight glass, the sensors and a return to the main tank or drain via a second 3-way valve (Figure 1).

The rig was designed to allow a volume of liquid to be released into the flow of another liquid. A 3-way gate valve was used to change from liquid to liquid in order to ensure that minimal initial mixing and dispersion occurred at the point of changeover.

The sensors under evaluation were installed within a straight run of pipe to ensure that the flow regime had stabilised by the time the interface region passed them. A sight glass was installed upstream of the sensors to enable a visual confirmation of the progress and nature of the interface. This also enabled manual triggering of the datalogging system prior to the arrival of the interface at the sensors.

The flowrig was operated as follows:

Water was used as the main liquid in all cases. The rig and sensors were allowed to stabilise at the required flowrate and temperature. The second liquid was filled into the secondary tank at the same temperature as the water in the main tank. When the sensor readings had stabilised, the 3-way valve between the tanks was switched rapidly from the main tank to the secondary tank. When the secondary tank was nearly drained, the 3-way valve was switched back to the main tank. This had the effect of creating two interfaces: water/liquid and liquid/water. While the secondary liquid was flowing in the system the return flow was diverted to drain, otherwise it was allowed to flow back to the main tank. The temperature of both tanks were monitored to ensure that water and liquid temperatures were no more than 1-2°C apart from when the trial commenced. Flowrates were monitored using an electro-magnetic flowmeter (Krone Altometer, Krone Measurement and Control Ltd, Brackmills, Northampton) mounted in the return leg of the pipework.

The sensors were mounted into a short length of pipe which was tilted slightly such that the downstream end was higher than the upstream end. This was done to reduce the likelihood of air bubbles being trapped within the sensors leading to false readings, particularly on the upper elements of the conductance probe. The ultrasonic sensor was oriented such that the signal path axis was horizontal. The temperature sensor was mounted vertically from above the pipe and the conductance probe was mounted vertically from below the pipe. The construction of the prototype sensors is described in more detail below.

2.2 Conductance Probe

The conductance probe was designed to simultaneously measure the conductance within the passing liquid stream at a number of locations across the diameter of the pipe. The probe was based on a fibreglass board former, 1.6mm thick, to which were attached eleven equally spaced platinum wire electrodes (Merck Ltd., Lutterworth, Leics). The wire was 0.5mm in diameter and the electrodes approximately 5mm long. The electrodes were configured such that any sensing electrode had a common electrode on either side of it, thus ensuring a uniform electric field shape for all sensing electrodes. The layout of the probe along with the electrical connections is shown in Figure 2. The immersed part of the probe was made as streamlined as possible to minimise any effect on liquid flow behaviour. The parts of the probe other than the electrodes themselves were coated in conformal coating to provide electrical isolation. The probe was assembled into a threaded fitting capable of being installed into a ½" BSP boss welded into the pipe wall. A silicone rubber (Sylgard 182, R.S. Components Limited, Corby, Northamptonshire) bung was moulded around the former in the threaded fitting to locate it securely and to prevent any liquid from entering the fitting. The bung was shaped to provide a surface flush to the pipe wall on the inside of the pipe so as to minimise turbulence at the point where the probe entered the pipe. The length of the former was set such that it rested on the opposite wall of the pipe when correctly located with the distance from the pipe wall to the first electrode on each end of the probe being equal.

The probe was fitted in the pipe such that the former was vertical and the fitting was beneath the pipe. This was done to reduce any possibility of air being trapped in the fitting due to a less than ideal fit being achieved between the fitting, the silicone rubber bung and the pipe wall.

2.2.1 Signal Processing

The conductance probe was connected to a power supply and a general purpose analogue/digital input/output card (Blue Chip ADC-42, Farnell Electronic Components Limited, Canal Road, Leeds) installed in a PC, as shown in Figure 3. The conductance could be simultaneously measured over the five zones using this technique. The power supply voltage was determined by trial and error to give the best resolution for the minimum amount of power in the probe. The current was minimised to prevent the build-up of excessive deposits on the electrodes and to reduce heat dissipation in the probe resistors.

2.2.2 Signal Interpretation

Initial development work with the probe showed that two important parameters with respect to interfaces could be deduced from the simple time/conductance data obtained from the probe. The point on the time axis at which conductance first begins to change for any zone within the probe indicates the time of arrival of the interface region. Thus by observing the times at which the different zones of the sensor register a change relative to each other the shape or profile of the leading edge of the interface region can be determined. Assuming that all zones in the probe give the same reading of conductance for a given liquid, the relative changes in signal amplitude will provide information concerning the dilutions between the liquids in the interface region.

The signal processing required for this interpretation was carried out in the PC using programs written in GWBASIC.

2.3 Ultrasonic Sensor

The configuration chosen for the ultrasonic sensor was the transmission system in which transducers arranged opposite each other across the diameter of the pipe were used to transmit and receive pulses of ultrasound via the liquid within the pipe. This enabled the passage of the interface to be observed as a change in time of flight or attenuation of the ultrasound signal. This approach differed from the conductance probe in that it allowed only an average reading for the sensing volume to be measured. The layout of the sensor is shown in Figure 4. Since the trials were all carried out at room temperatures, no special precautions were required to isolate the transducers form the effects of processing temperatures. Changes in the temperature of the product change the time of flight of the ultrasound across the pipe. Compensation for this effect is possible. However, great care was taken to ensure that both liquids were at the same temperature during a trial, thus eliminating the need for compensation. A thermocouple probe was fitted in the pipe with its tip on the centre line of the pipe adjacent to the ultrasonic signal path to monitor the liquid temperatures throughout the trial.

The transducers used were 1.25MHz thickness gauge types (Sonatest SLH1-25, Sonatest plc., Old Wolverton, Milton Keynes). These were clamped to the ends of the stainless steel waveguides which were in turn welded into the pipe wall with approximately 5mm of the guide protruding into the pipe. Ultrasonic coupling gel was used to couple the transducers to the waveguides.

The sensor was oriented such that the ultrasonic signal path was horizontal. This was to avoid problems with signal loss due to air bubbles becoming trapped at the top of the pipe.

2.3.1 Signal Generation and Processing

A pulse generator provided square wave pulses of 800ns duration and 100V amplitude to the transmitting transducer at a pulse repetition rate of 10KHz. The signal from the receiving transducer was pre-amplified by a Hewlett Packard HP8114 wideband amplifier with a gain of 20dB and then further amplified and filtered using circuits developed at CCFRA with a total gain available of 50dB. A gating circuit was used to select specific parts of the received waveform for further processing. Amplitude and time of flight information was derived from the selected signal using a circuit specially developed for this purpose. The output from the circuit was in the form of parallel digital and analogue data and was input to a PC via the general purpose analogue/digital input/output card. This was also used to input data from the conductance probe and temperature sensor. The ultrasonic signal processing hardware layout is shown in Figure 5.

2.3.2 Signal Interpretation

The sensor monitored the change in signal within a volume defined by the diameter of the ultrasonic beam across the pipe. The waveguides have a diameter of 20mm and, since the sensors were operated in the near-field range, the sensing volume will have a similar diameter to this. Depending on the physical properties of the two liquids, both the amplitude and time of flight of the signal will vary in accordance with the change in dilution as seen within the sensing volume. Some combinations of liquids exhibited large changes in signal attenuation at the interface of the liquids while other combinations exhibited large changes in time of flight of the ultrasound.

2.4 Temperature Sensor

A temperature probe was installed in the sensor pipe adjacent to the ultrasound sensor. The probe consisted of a thin wire type K thermocouple junction contained in a stainless steel sheath of 1.5mm O/D (R.S. Components Limited, Corby, Northamptonshire). It was installed in a gland assembly welded into the pipe wall and was arranged such that the sensitive tip of the probe was on the centre-line of the pipe, adjacent to and upstream of the ultrasonic signal path. The probe possessed a sufficiently rapid speed of response to allow the recording of temperature changes between liquids at high flowrates.

2.5 Software

A PC was used for data capture, signal processing and analysis. A general purpose interface card was used to read in the sensor signals. These included parallel digital data for the ultrasonic time of flight signal, analogue voltages for the ultrasonic amplitude signal and conductance sensors, and the Type K thermocouple probe for temperature compensation for the ultrasound sensor. A program in BASIC was written for the sensor system. This program had two main functions: to filter and process the incoming signals to remove noise, and to present the data on screen and save it in an ASCII file for subsequent analysis in a spreadsheet. The sampling rate for the complete sensor system was set at one second in order to allow all readings to stabilise before being taken. The elements of the program are discussed below in more detail.

2.5.1 Conductance Probe

The incoming data from the probe was read twenty times in succession and the values for each probe zone averaged to remove excessive sensor noise. The data was then passed to the screen for display and to a disk file for storage.

2.5.2 Ultrasonic Sensor

The time of flight data was read in as two groups of two 8 bit bytes, the first group of bytes corresponding to the time of the leading edge of the sampled signal with respect to a fixed reference and the second corresponding to the trailing edge of the sampled signal. The times were converted to microseconds and averaged. The data was passed to the screen for display and to a disk file for storage.

Amplitude data was read in as a single analogue voltage equivalent to the positive peak signal level of the sampled signal. Since an averaging effect was inherent in the signal processing hardware no further averaging was required. The data was passed to the screen for display and to a disk file for storage.

2.5.3 Temperature

The temperature data from the type K thermocouple was input to the PC via a cold junction compensation module as a linearised analogue voltage. Twenty consecutive readings were taken and the average calculated to filter out noise from the signal. The probe system was calibrated against thermometers of known accuracy and a calibration equation derived to convert the voltage to temperature. The temperature data was passed to the screen for display and to a disk file for storage.

2.6 Liquids

To provide a common reference for all tests it was decided to use water as the main liquid in all experiments. Experience showed that water is a reasonable conductor of electricity and ultrasound and it thus provided a useful reference from which both positive and negative changes in signal parameters may easily be observed.

A range of secondary liquids was chosen to broadly simulate a range of liquid food products and cleaning solutions. The liquids used are summarised in Table 1.

Table 1

Liquids Used in Experimental Trials

Liquid Solution	
Type	**Strength**
Milk	Full cream
Milk	semi-skimmed
Starch (1)	2% w/v
Starch	4% w/v
Starch	6% w/v
Glucose (2)	10% w/v
Glucose	50% w/v
Caustic soln. (3)	2% v/v
Caustic soln.	5% v/v
Citric acid (4)	0.5% v/v
Citric acid	1.0% v/v
Water	****

Notes:

(1) Starch was Colflo 67 (National Starch Limited, Trafford Park, Manchester).

(2) Glucose was D-Glucose 'AnalaR' (Merck Limited, Magna Park, Lutterworth, Leicestershire).

(3) Caustic solution was Diversey Diverflow 3 (Diversey Limited, Cotes Park Industrial Estate, Somercoates, Derbyshire).

(4) Citric acid was anhydrous food grade citric acid (Ellis & Everard Chemicals Limited, Yate, Nr. Bristol).

3. EXPERIMENTS AND RESULTS

3.1 Experiments

For all experiments the basic format was kept constant; a pulse of secondary liquid was introduced into a flow of main liquid (water in all cases) thus creating two interfaces as described in section 2.1 above. The secondary liquids and flowrates were the only varied parameters. The liquids used have been described in section 2.6 above. The flowrates used were 10 litres/min, 50 litres/min and 110 litres/min. The latter flowrate corresponds to a liquid velocity through the sensor of 1.2 ms^{-1} which is representative of flowrates normally used during CIP operations. Only the caustic and citric solutions were used at this flowrate. Table 2 shows the experimental matrix used.

Table 2

Experimental Matrix

Liquid Type	Flowrate (litres/min)		
	10	50	110
Full cream milk	Y	Y	N
Semi-skimmed milk	Y	Y	N
2% w/v starch	Y	Y	N
4% w/v starch	Y	Y	N
6% w/v starch	Y	Y	N
10% w/v glucose	Y	Y	N
50% w/v glucose	Y	Y	N
2% v/v caustic soln.	Y	Y	Y
5% v/v caustic soln.	Y	Y	Y
0.5% v/v citric acid	Y	Y	Y
1.0% v/v citric acid	Y	Y	Y

3.2 Results

Graphs showing typical sensor responses for all experiments are contained in Appendix 1. These are discussed in more detail for each liquid below.

3.2.1 Milk (Graphs 1 to 4)

For full cream milk, at both flowrates the ultrasonic signal was greatly attenuated by the passage of the interface regions and remained very weak during its passage through the sensor to the extent that the time of flight signal was unusable. The amplitude signal was more reliable although the relative change in signal amplitude was small. The conductance probe gave a small but reliable change in signal with some indication of the relative dilutions in the interface regions and also in the bulk of the milk sample.

Similar results were obtained for semi-skimmed milk. The changes in time of flight shown on the graphs for both milk types was due to the loss of the signal.

3.2.2 Starch (Graphs 5 to 10)

For all starch solutions at both flowrates, clear but weak signals were obtained from the ultrasonic sensor, the time of flight signal being clearer than the amplitude signal. In all cases the conductance signal was very poor, being weak, noisy and unclear.

3.2.3 Glucose (Graphs 11 to 14)

At 50 litres/min the 50% w/v solution gave clear strong results from the ultrasonic sensor and the conductance sensor. The 10% w/v solution gave similarly clear but weaker signals from the ultrasound sensor and considerably weaker signal from the conductance probe.

At 10 litres/min all sensors produced very weak, noisy and ill defined signals for both solution strengths with the clearest indication coming from the time of flight signal.

3.2.4 Caustic Solutions (Graphs 15 to 20)

For both caustic solutions, at a flowrate of 110 litres/min clear but weak signals were obtained from the ultrasonic sensor. Clear and large signals were obtained from the conductance sensor.

At 50 litres/min the ultrasonic time of flight signal was clearer while the amplitude signal became weaker. The conductance sensor signals remained clear but became less well defined.

At 10 litres/min the ultrasonic time of flight signals remained clear while the amplitude signal became noisier. The conductance signal increased in amplitude but became noisier and less well defined.

3.2.5 Citric Acid Solutions (Graphs 21 to 26)

For both 0.5% w/v and 1.0% w/v citric acid solutions, at 110 litres/min, the ultrasonic signals were weak and indistinct with no clear indication of the passage of the interfaces or the differences in the liquids. The conductance sensor gave a very clear indication of the difference between the liquids.

At 50 litres/min the ultrasonic signals gave a similarly weak response but with a clearer indication of the leading interface. The conductance signal was weaker and less well defined.

At 10 litres/min the ultrasonic time of flight signal gave a very clear indication of the difference between the liquids whereas the amplitude signal showed no discernible change. The conductance probe showed a weak and noisy response.

3.3 Discussion

The results from these tests showed that the ultrasound sensor was better suited to liquid combinations which exhibited large differences in rheological properties. The conductance sensor was more suited to the cleaning solutions which were rheologically very similar to water.

The performance of both sensors generally improved with increasing flowrate for any given combination of liquids. There were exceptions to this trend, notably the citric acid solutions which showed an improvement in the time of flight measurements at lower flowrates.

Interpretation of the readings from the sensors was complicated because of the differences in densities and rheological properties of the liquids. Where the second liquid was of significantly different density to the first, 50% w/v glucose and water for example, the glucose sank to the bottom of the pipe and formed a puddle over which the water flowed. This puddle was very slow to clear, especially at the lower flowrate of 10 litres/min. The results showed that the conductance sensor was insensitive to glucose at low flowrates and the horizontal orientation of the ultrasound sensor meant that the puddle of glucose was outside the sensing volume, i.e. neither sensor was able to indicate the presence of the puddle. However, at the higher flowrate of 50 litre/min both sensors showed greater sensitivity to the glucose, but, in this case, the puddling effect was greatly reduced and quicker to clear.

3.3.1 Ultrasound Sensor

The ultrasound sensor was only able to provide an indication of the average state of the liquid within its sensing volume, i.e the volume of liquid directly between the transducers. Furthermore it relied on a number of assumptions the pipe being filled with liquids, no particulates or gas bubbles being present within the liquids, and the liquids having different acoustic properties. Also, it was necessary to compensate the time of flight measurements for the effects of change in liquid temperature on sound velocity. These requirements put some limits on the potential uses for the sensing technique.

In some trials, where the liquids were immiscible and of different acoustic impedance, clear signals were obtained from both liquids in isolation but signals were severely attenuated or lost entirely as the interface region passed. The immiscibility of the liquids resulted in small zones of one liquid within the other. The boundaries of these zones caused high levels of attenuation due to reflection and scattering of the ultrasound. The loss of signal may be considered as a sensing parameter, although this is unwise since signal loss may result from a number of causes including sensor malfunction.

The results for the ultrasound sensor showed that, when the requirements are met, the sensor was able to provide an indication of the passage of an interface region through the sensor and also provide some indication of the nature of the liquid in the pipe.

It is conceivable that interface detection could be combined with other on-line measurements using ultrasound in this fashion, e.g density or flowrate.

3.3.2 Conductance Sensor

The conductance probe differed from the ultrasonic sensor in that it was able to provide a number of spot measurements across the diameter of the pipe. It provided two types of information about the interface. The point at which any element within the probe indicates a change in conductance provides an indication of the arrival time of the interface region at the sensor location. Any differences in the time in which the interface is detected by different elements within the sensor will reveal information about the shape of the interface which will be influenced by the flow regime within the pipe. The magnitude of the change in the conductance provides an indication of the dilution of the two liquids in the interface region. The time element of the signal may be of limited use in the case of interface detection for the purposes of ensuring that one liquid is replaced by another. However, it will have applications in other areas; this is discussed in section 5, Future Work.

The overall results tend to show that the conductance probe was better suited to the cleaning solutions and the ultrasonic sensor was better suited to the food products. However, this is a broad generalisation and further studies would be required for specific liquid combinations to determine the most suitable technique.

To be of use in commercial applications both sensors would require substantial modification in terms of invasiveness and hygienic design. Both would require a careful choice of materials and construction techniques so as to minimise the possibility of fouling and ease of cleaning, especially during CIP operations. The conductance probe would require easy access for regular cleaning of the electrodes and also it would have to be shaped so as to minimise disruptions to the product flow. Furthermore, the effects of electrochemical corrosion of the sensor elements would have to be considered and it is likely that the probe itself would require periodic replacement or refurbishment. Also it would be necessary for relatively complex signal generation and monitoring hardware to operate the probe in order to minimise the effects of electrochemical erosion and deposition on the electrodes and prevent these effects from distorting the readings. The conductivity sensor may also require specific characterisation for a given product or range of products in terms of the likely range of conductance to be measured. The ultrasonic sensor would require similar development and it would also need compensating for the effects of change in liquid temperatures.

4. CONCLUSION

Two sensing techniques, ultrasound and electrical conductance, were evaluated in terms of their ability to detect and monitor liquid-liquid interfaces under on-line continuous flow conditions.

Both sensing techniques were able to detect and monitor the progress of interfaces under on-line conditions for some combinations of liquids. However, no clear patterns emerged from the results in terms of the techniques being best suited to certain products. The flowrate of the liquids was found to have considerable influence on the capabilities of sensors. As a general rule the sensors were found to operate more effectively at higher flowrates. At lower flowrates the signals became weaker and noisier. Furthermore, little variation in signals was obtained from different concentrations of the same liquids, for example 2, 4 and 6%w/v starch solutions showed similar results for any given flowrate. However, in the case of the 50% glucose solution at 10 litres/min, its high density (relative to water) resulted in it forming a puddle in the bottom of the pipe while the water flowed above it. The ultrasonic sensor was unable to detect this while orientated horizontally. This was not sensed reliably by the conductance probe either. This problem was not observed at the higher flowrate.

5. FUTURE WORK

There are two possible development routes for the sensing techniques described here; they could be further developed as outlined in the conclusions for use in commercial processes, and they could be developed as tools for use in understanding liquid flow regimes in continuous flow processes at an experimental level. As has already been stated, the conductance probe can be used for determining liquid residence times and also for monitoring flow profiles in terms of dilution strengths between a base liquid and a more, or less, conductive marker liquid with otherwise identical properties. This technique could be applied to the validation of models used to describe liquid flow.

The ultrasonic sensor is, by its nature, limited in terms of its range of potential applications. However, it is likely that developments in terms of the signals processing hardware and software of such a sensor would overcome some of the difficulties mentioned above. Its key benefit is that it could be made to be non-invasive with minimal impact on the cleanability and hygienic design aspects of the plant in which it was installed.

REFERENCES

Bozicevic, J. (1979). Liquid-Liquid Interface Transducer. Proceedings of the 8th Imeko Congress of the International Measurement Confederation, Part 1, 469-476.

Chan, C.K., Liang, N.Y. and Liu, W.C. (1993). Measurement of the Shape of a Liquid-Liquid Interface by the Method of Light Reflection, Rev. Sci. Instrumentation, 64 (3), 632-637.

Hoyt, M.M. (1979). Development in Sonic Interface Detection. ISA Transactions, 18 (1), 15.

Laycock, C.H. (1969). A Prototype Liquid-Liquid Interface Detector, Ultrasonics, July 1969, 193-194.

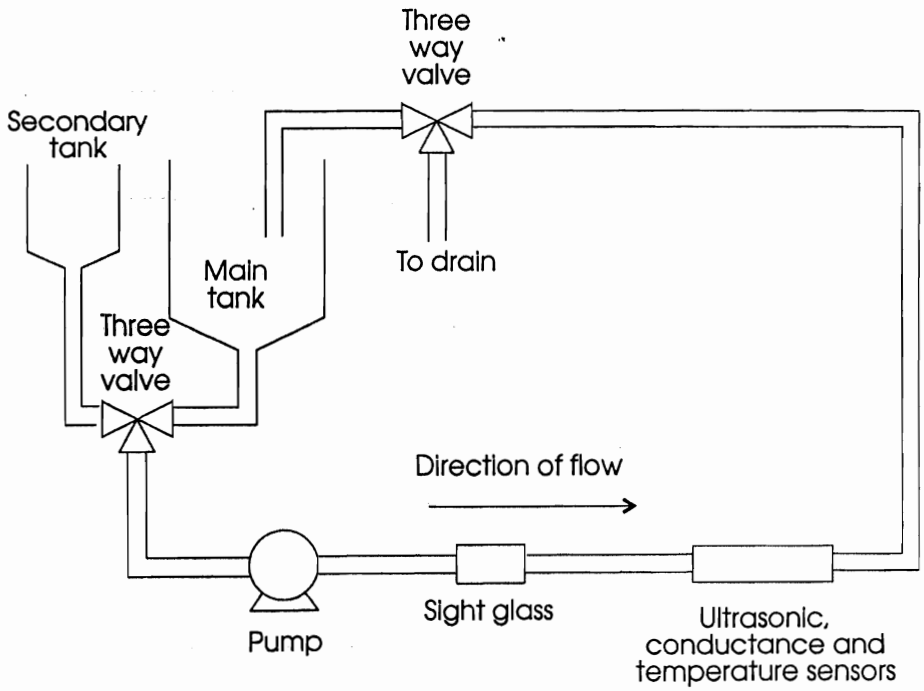


Figure 1

Layout of Experimental Flowrig

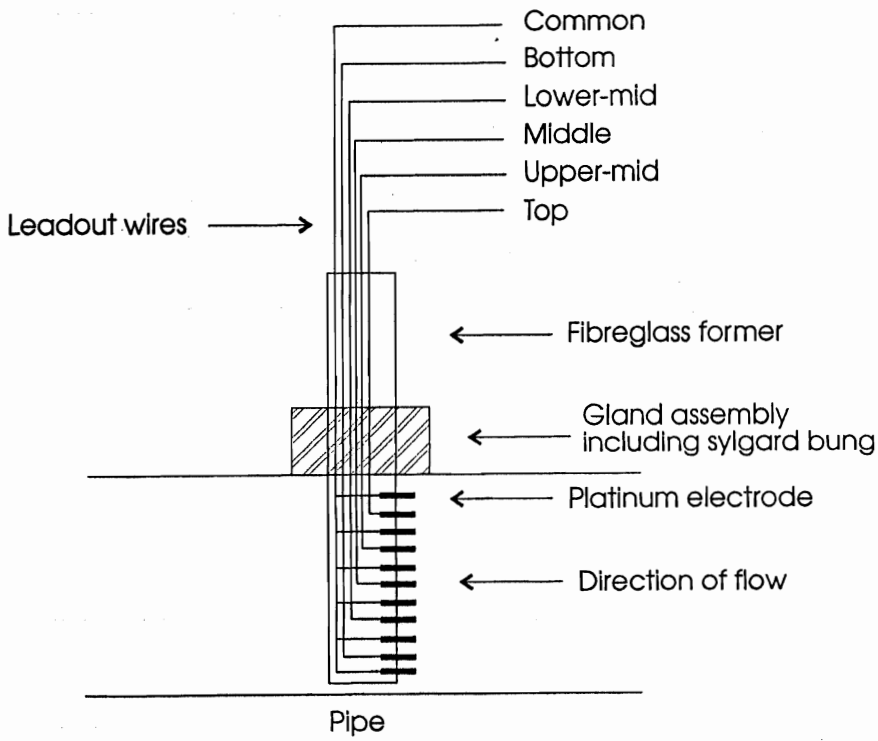


Figure 2

Construction of Conductance Probe and Method of Mounting in Pipe

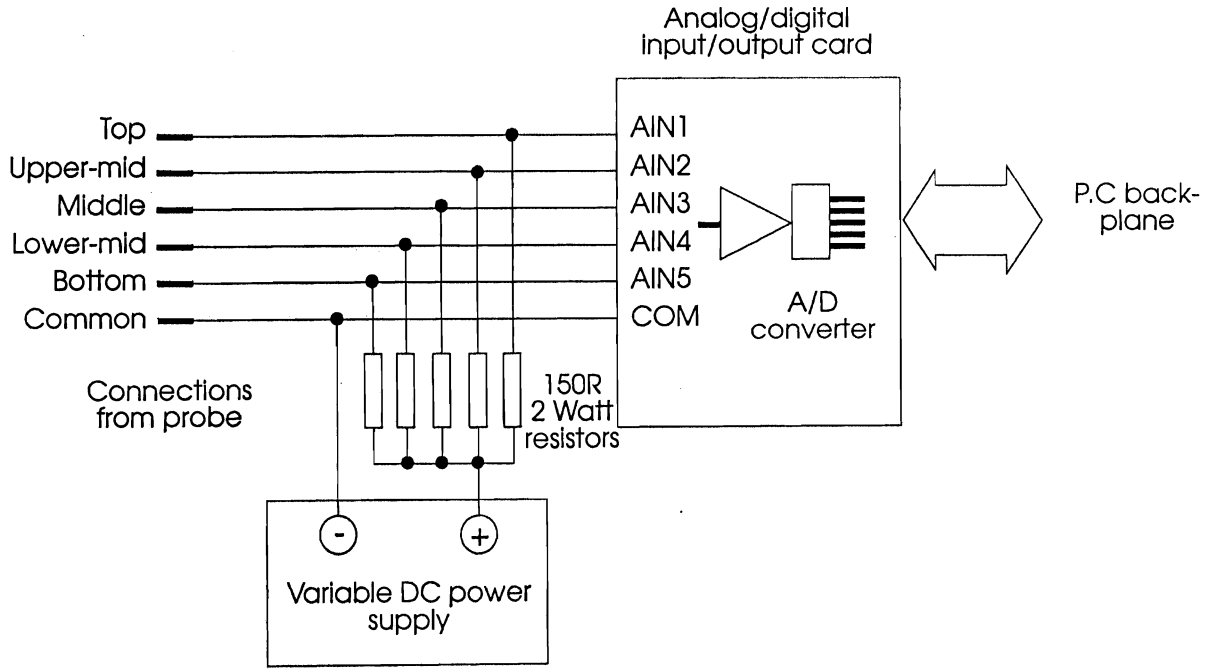


Figure 3

Connection Between Conductance Probe and Computer

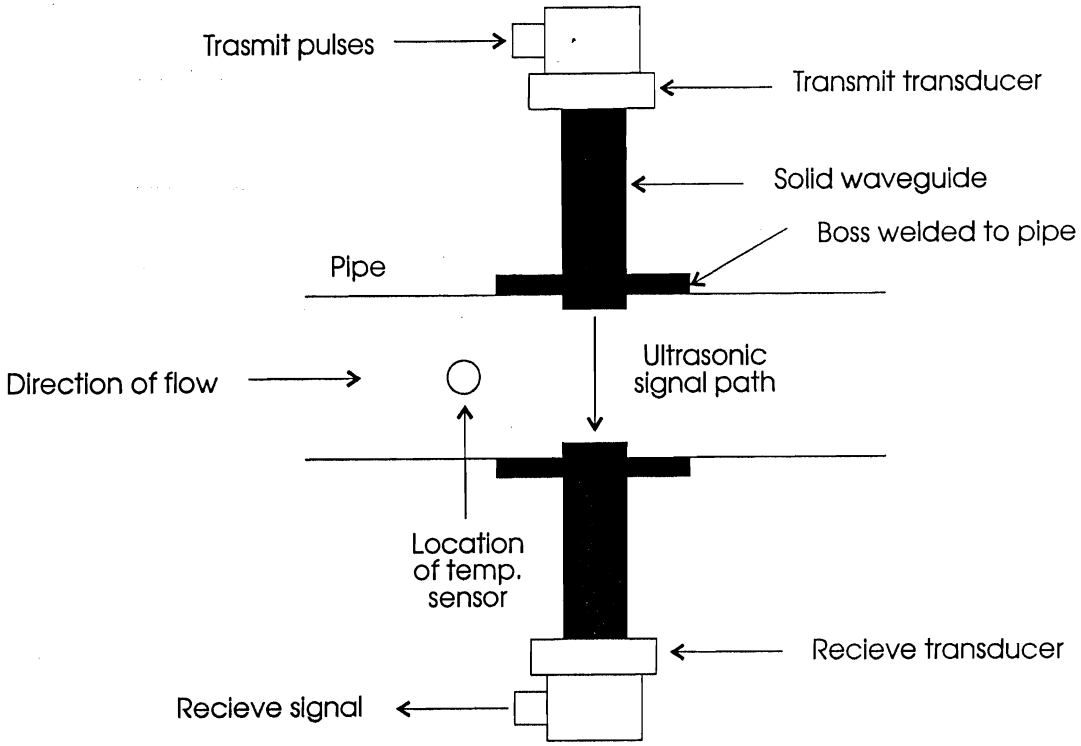


Figure 4

Construction of Ultrasonic Sensor

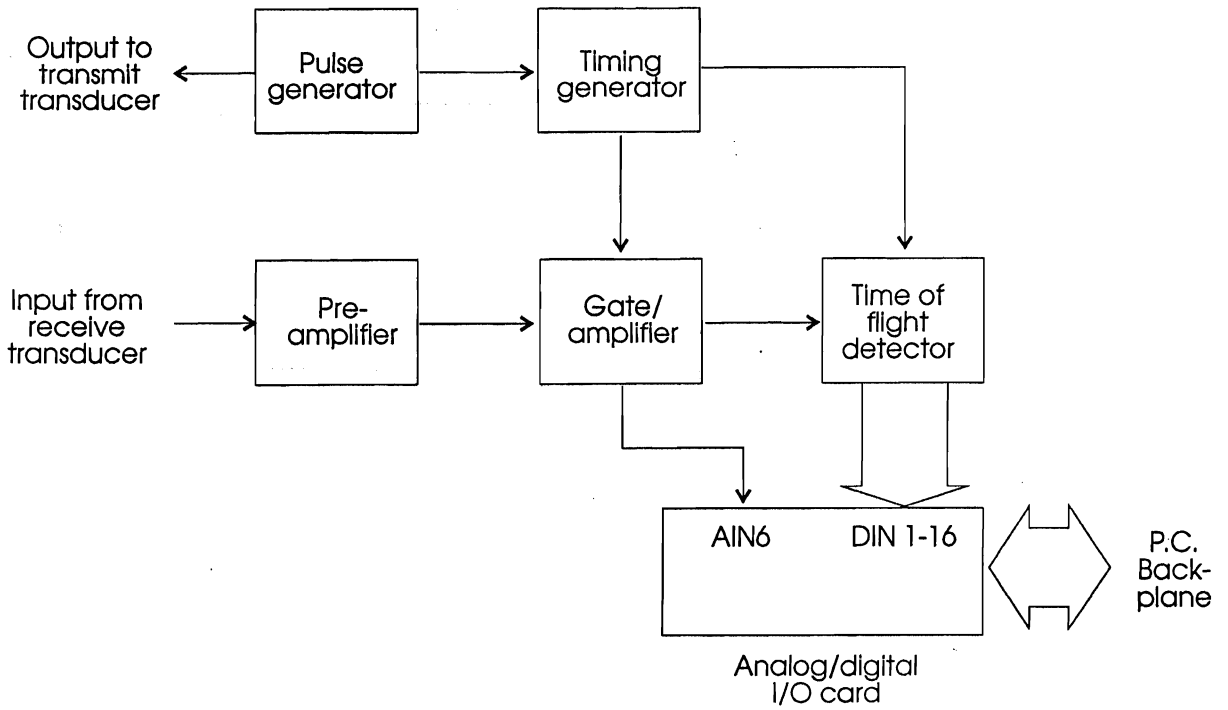
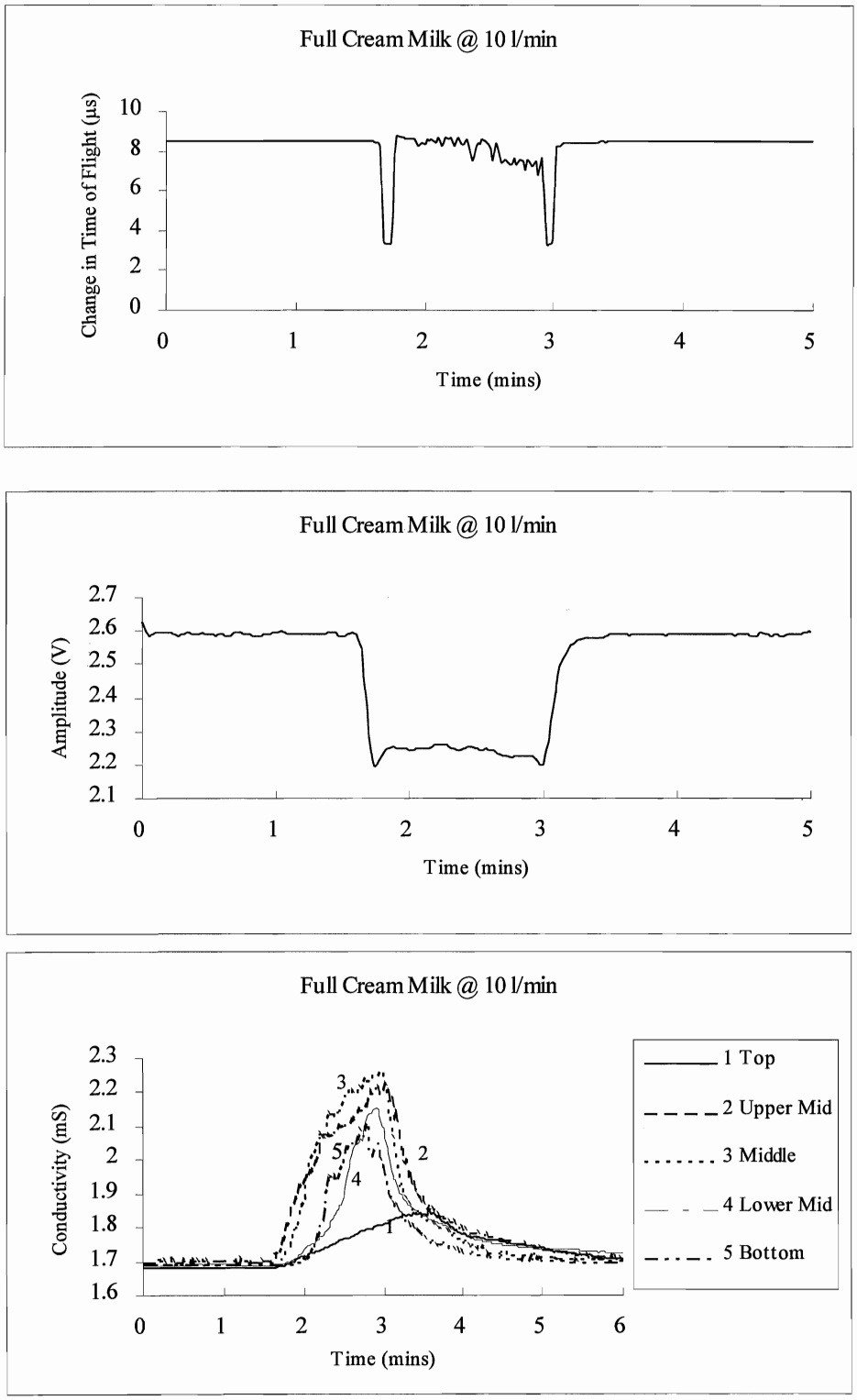


Figure 5

Layout of Signal Generation and Processing Hardware for Ultrasonic Sensor

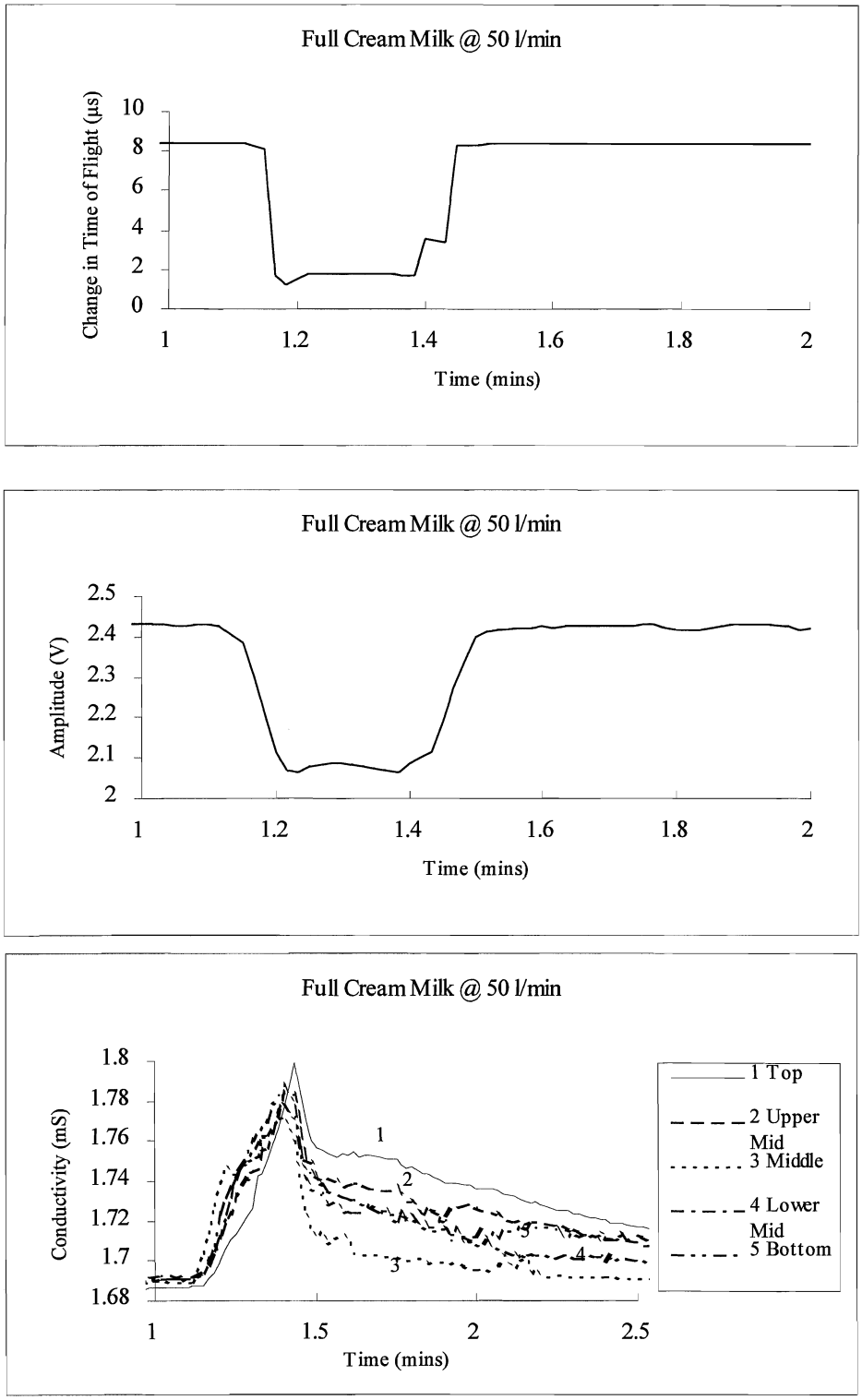
APPENDIX I

Three graphs are shown for each product type: conductance against time, ultrasonic time of flight against time and ultrasonic amplitude against time.



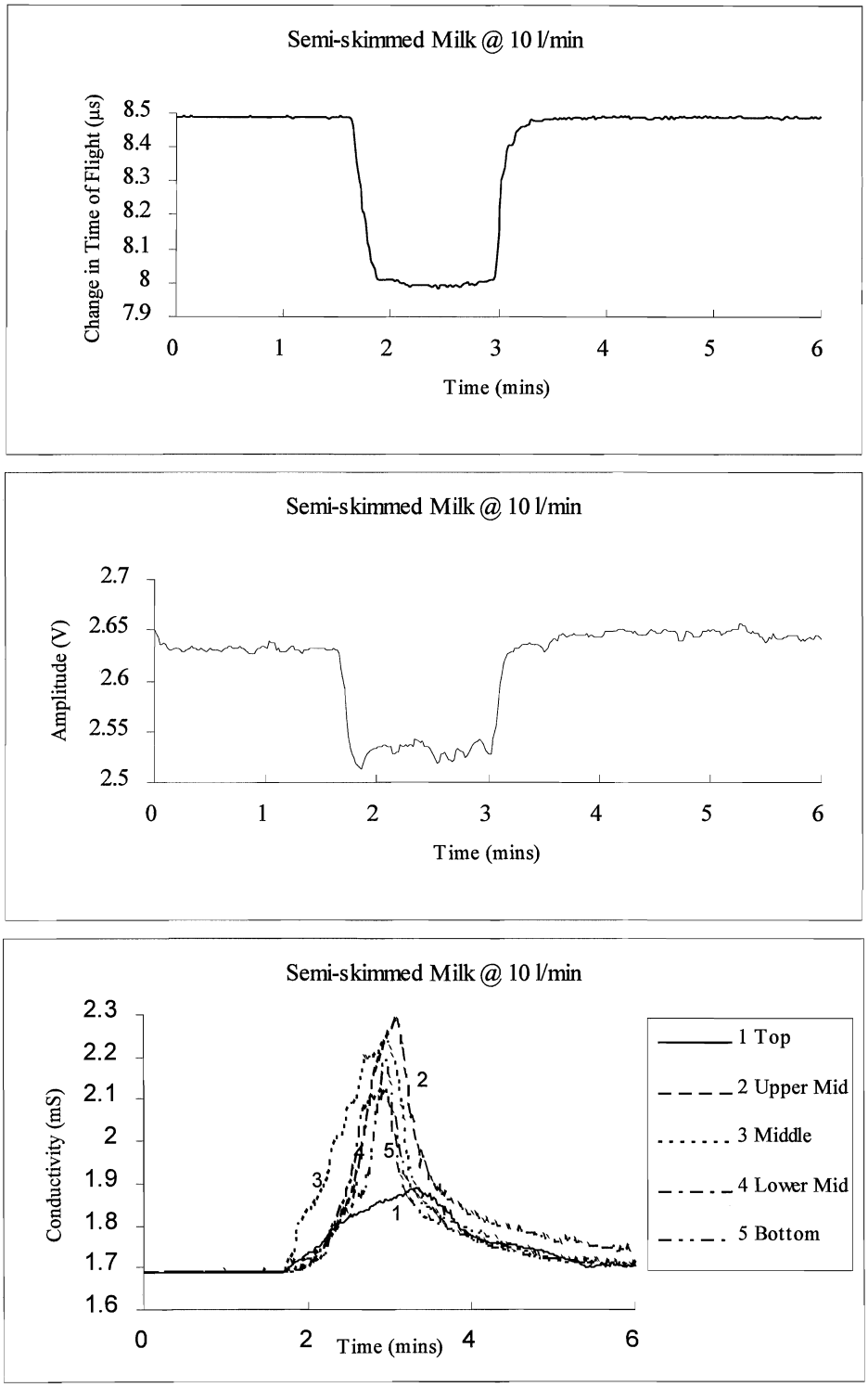
Graph 1: Full Cream Milk at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



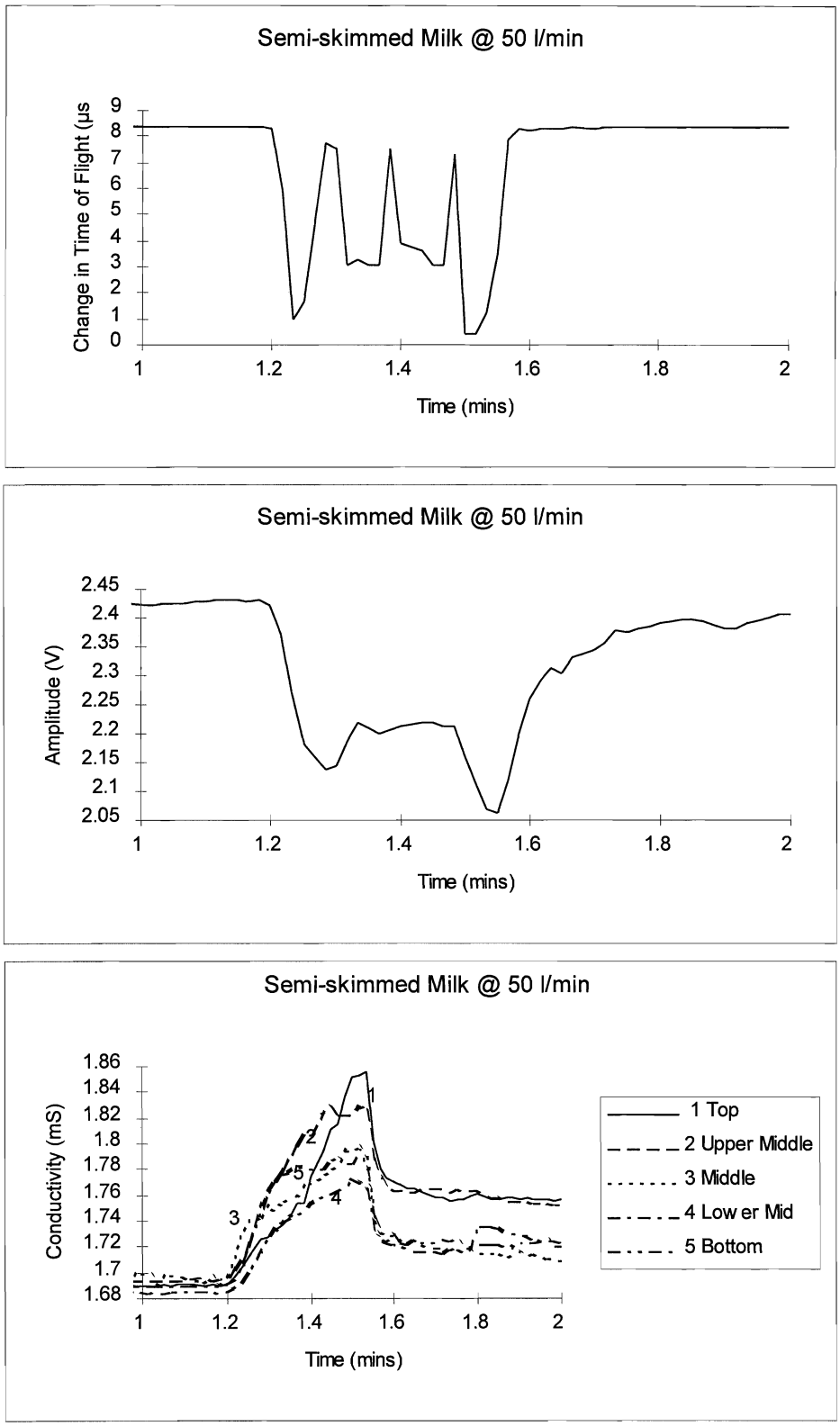
Graph 2: Full Cream Milk at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



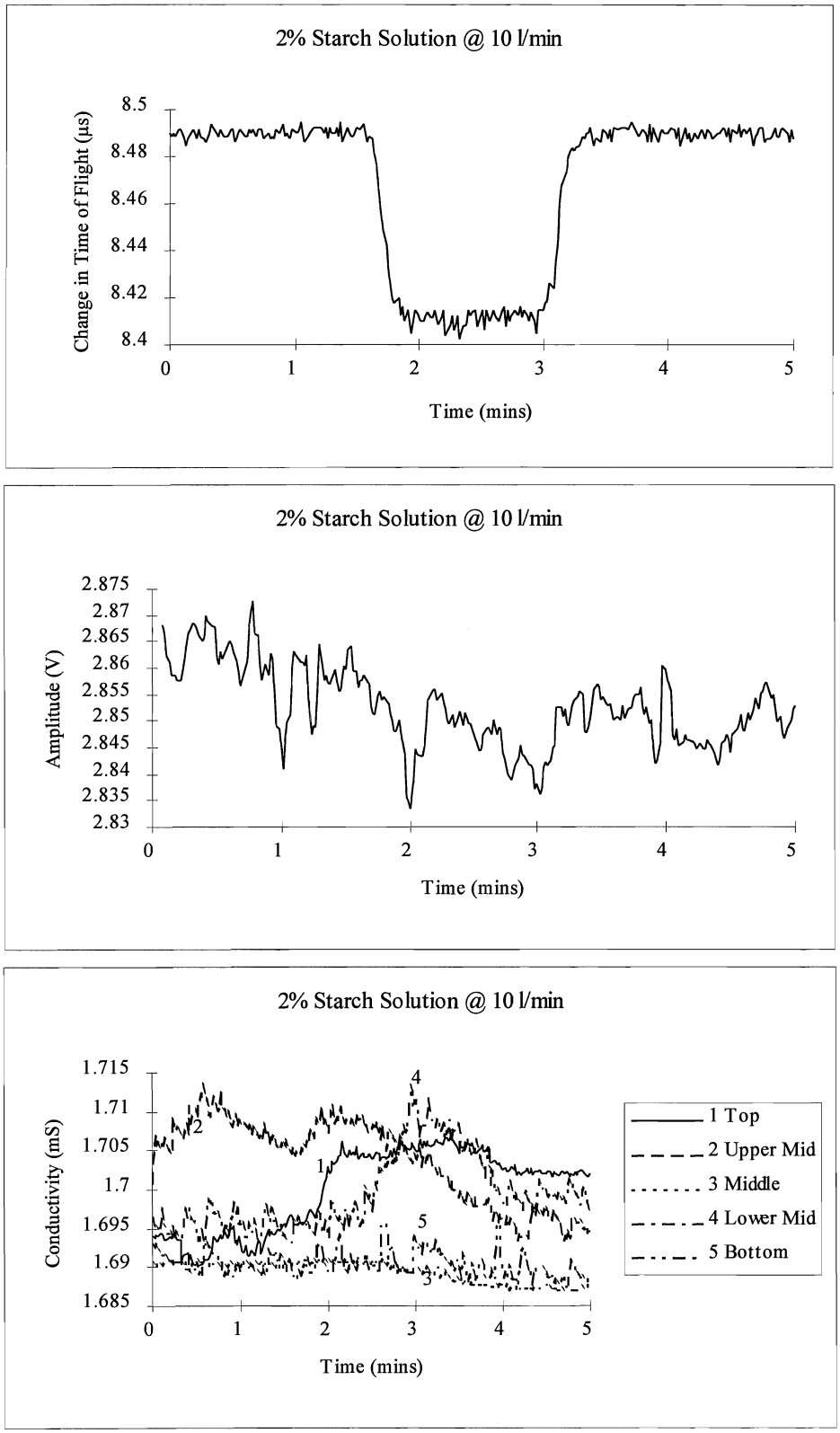
Graph 3: Semi-skimmed Milk at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor

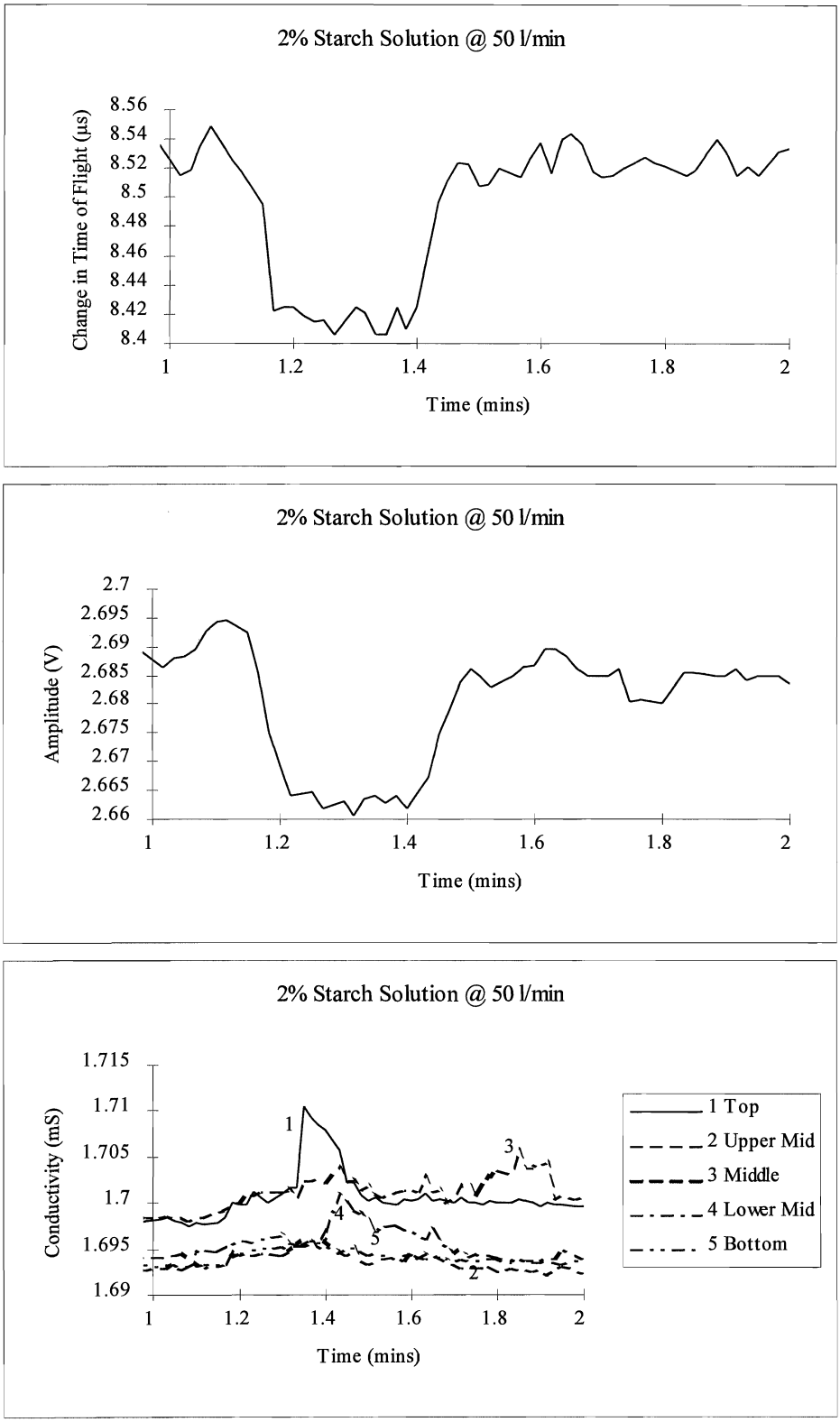


Graph 4: Semi-skimmed Milk at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor

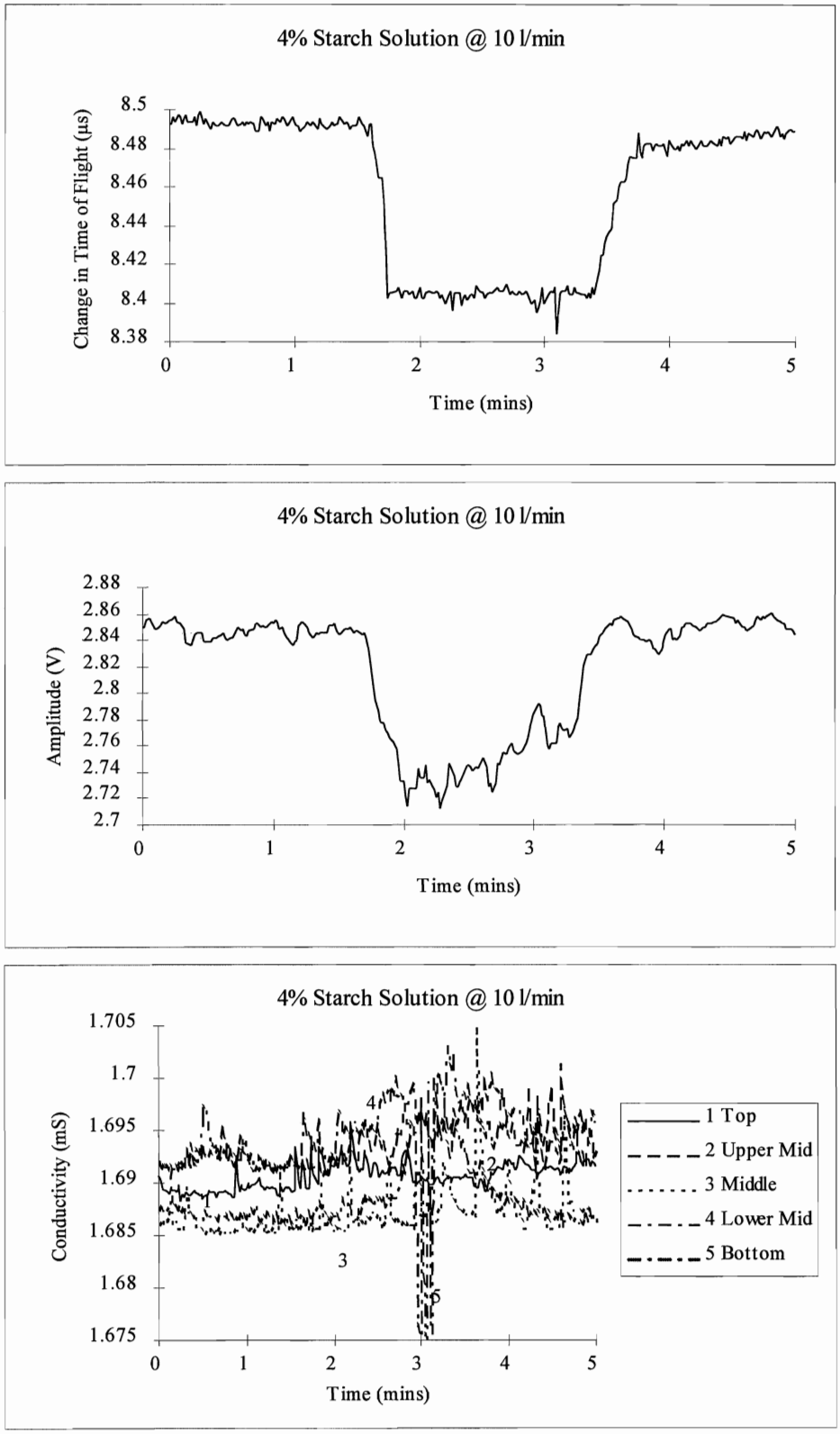


Graph 5: 2% Starch Solution at 10 Litres/min
Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



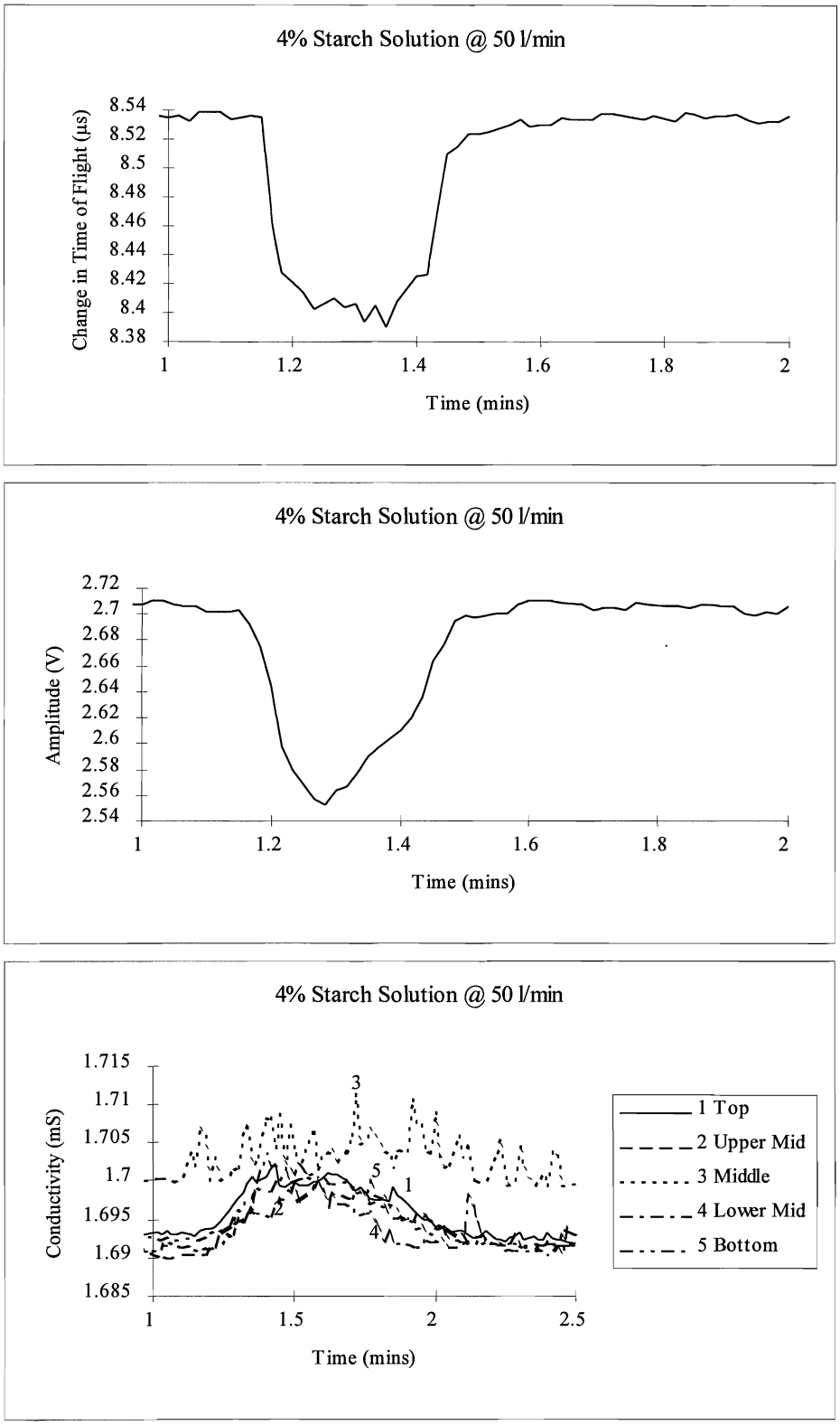
Graph 6: 2% Starch Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



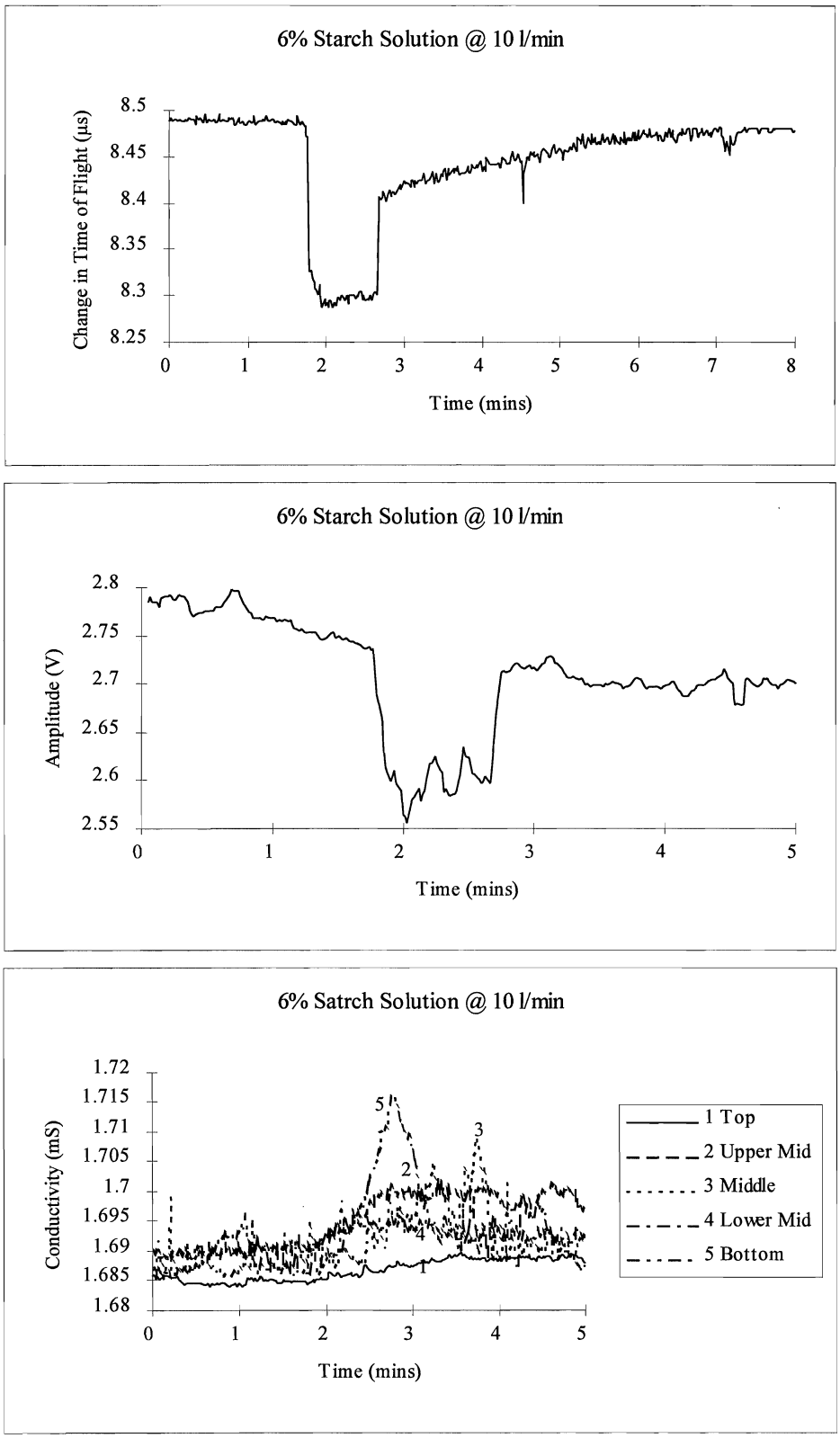
Graph 7: 4% Starch Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



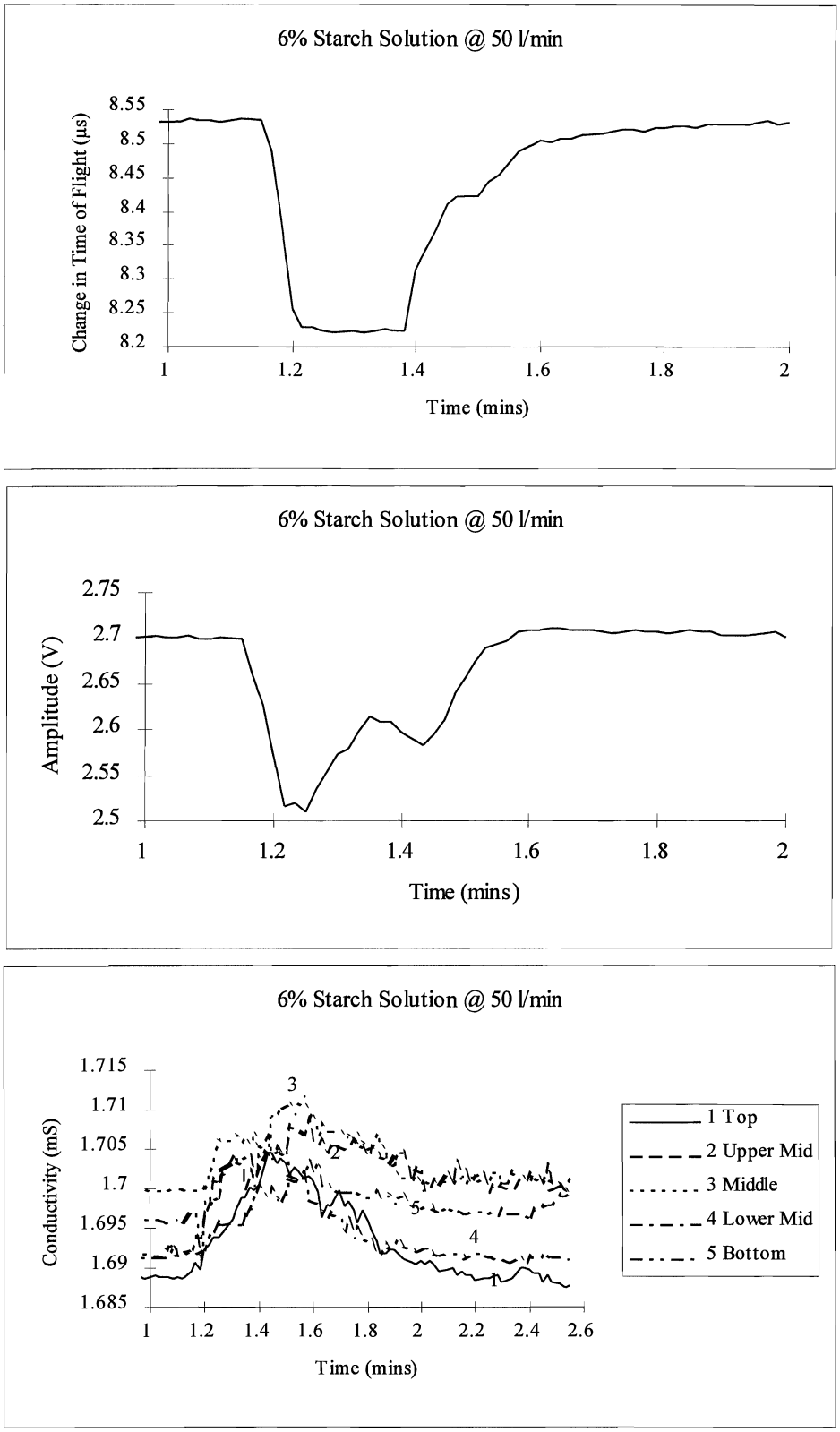
Graph 8: 4% Starch Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



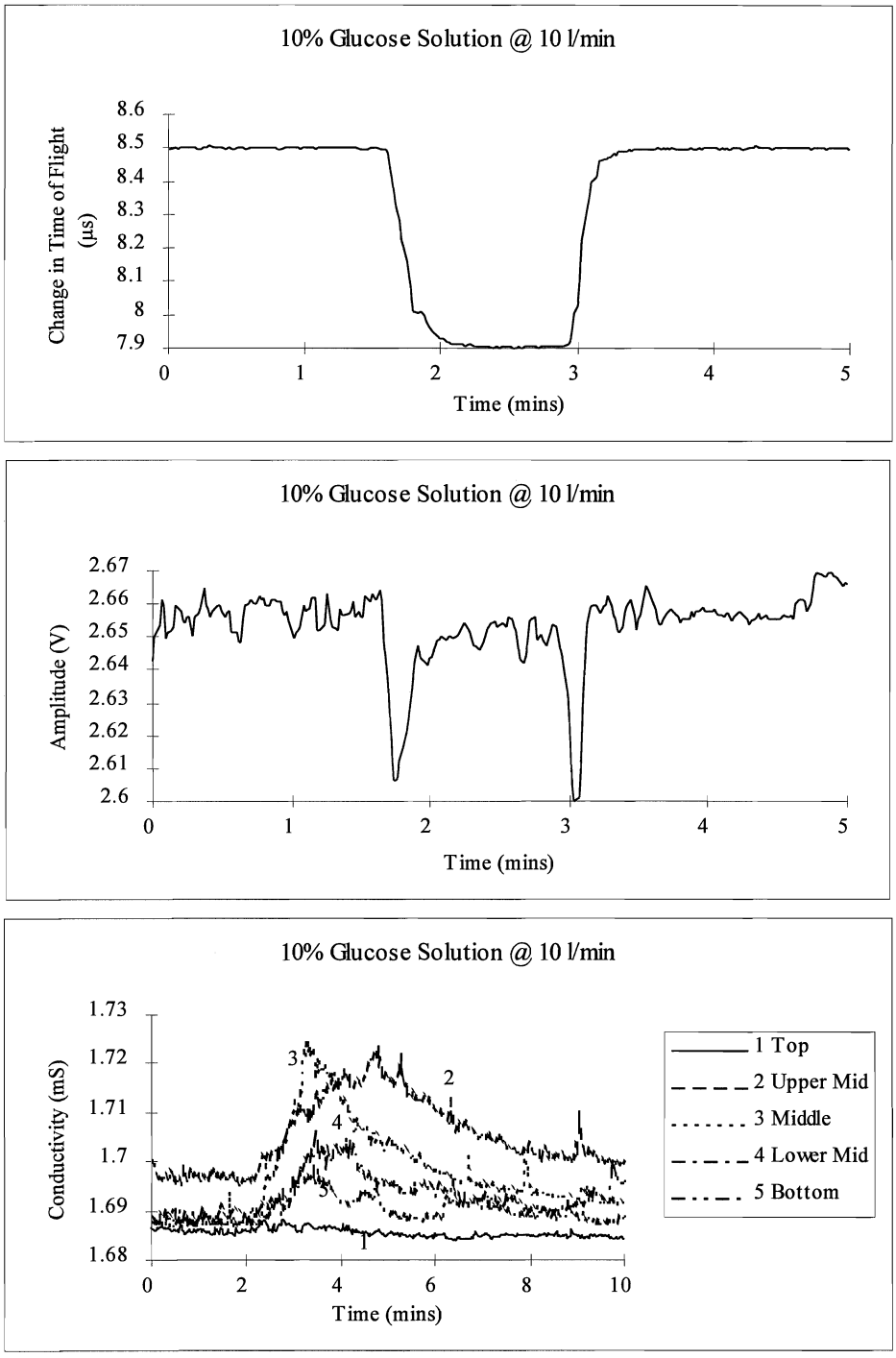
Graph 9: 6% Starch Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



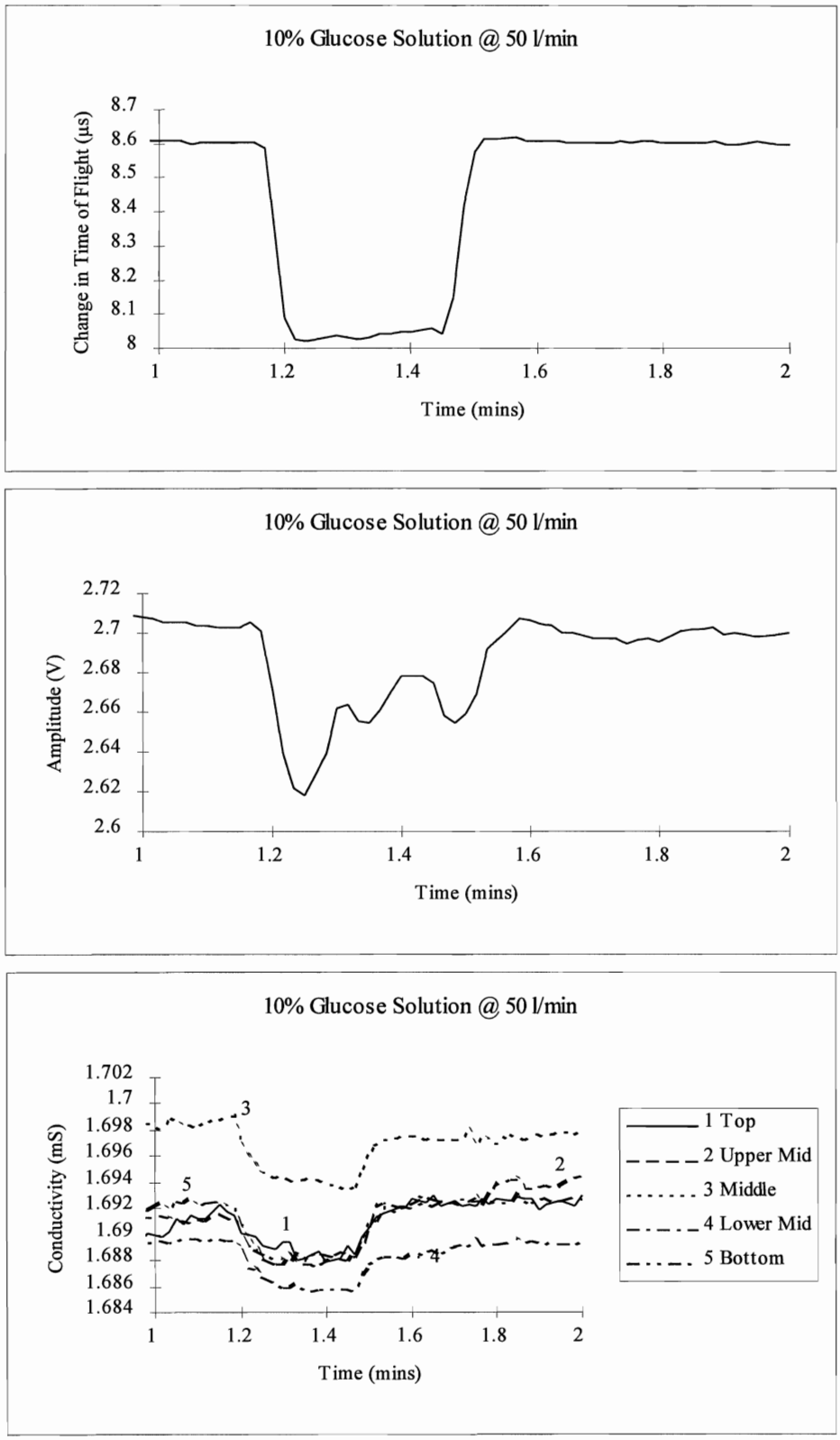
Graph 10: 6% Starch Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graphs from conductance sensor



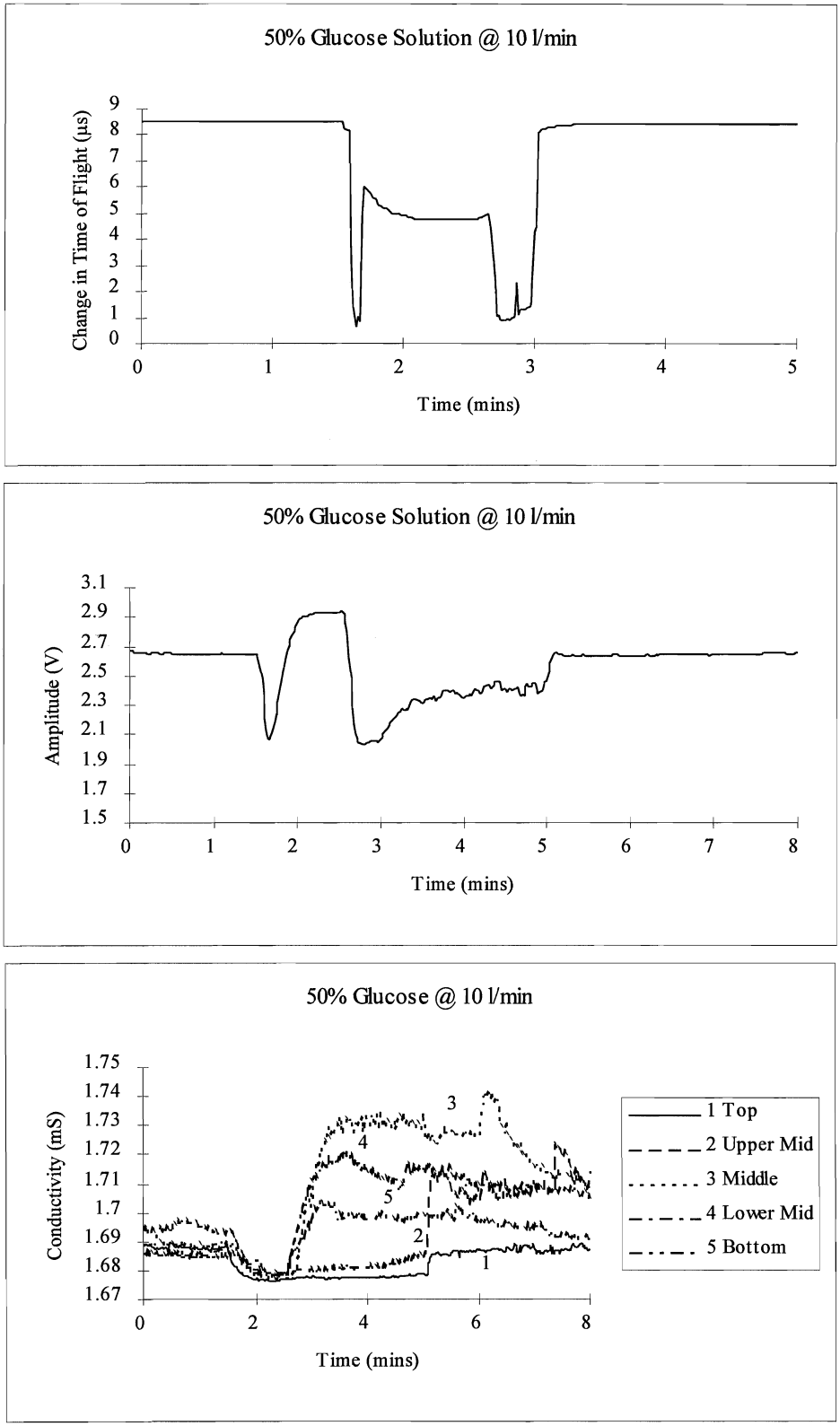
Graph 11: 10% Glucose Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



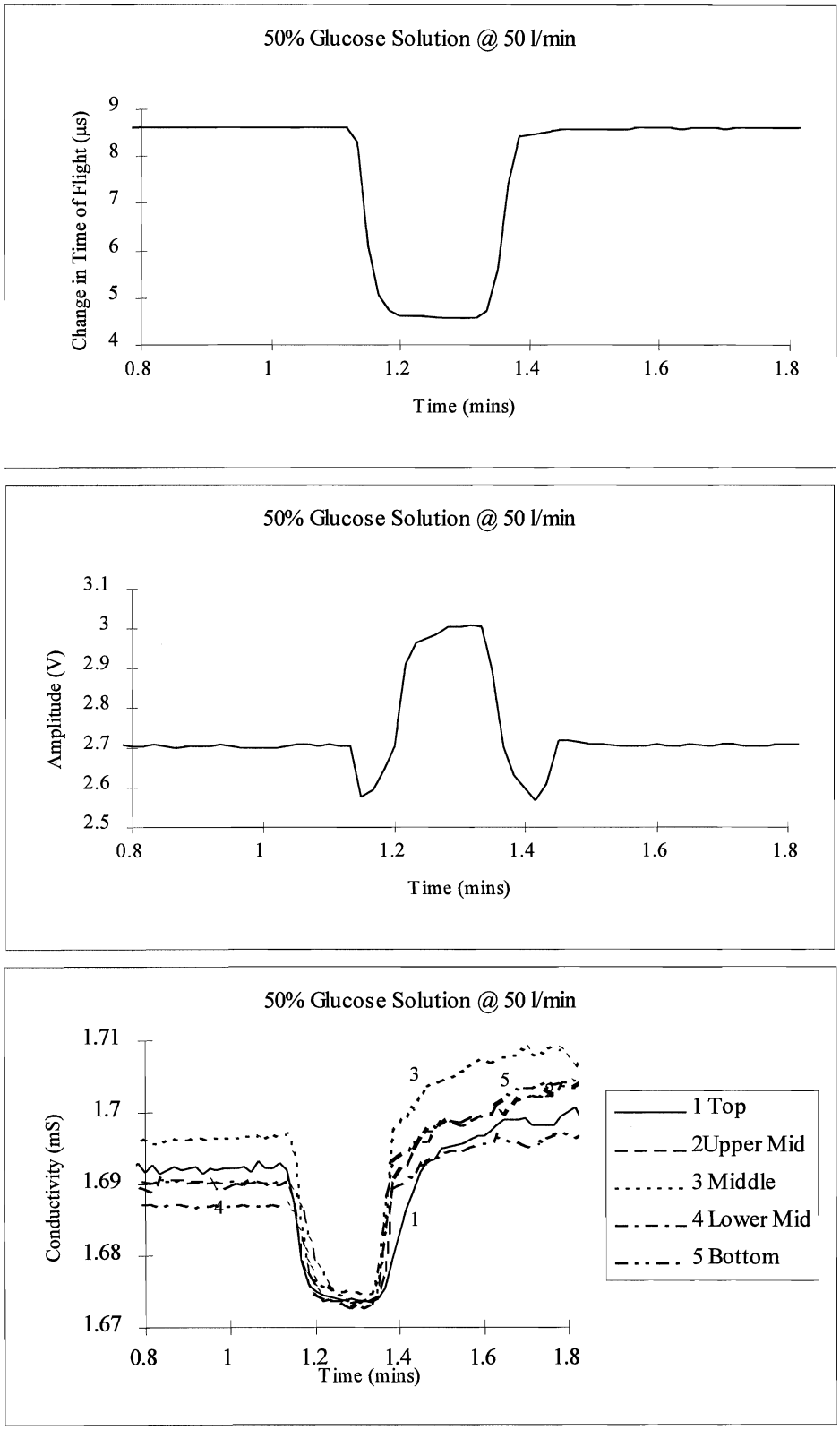
Graph 12: 10% Glucose Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



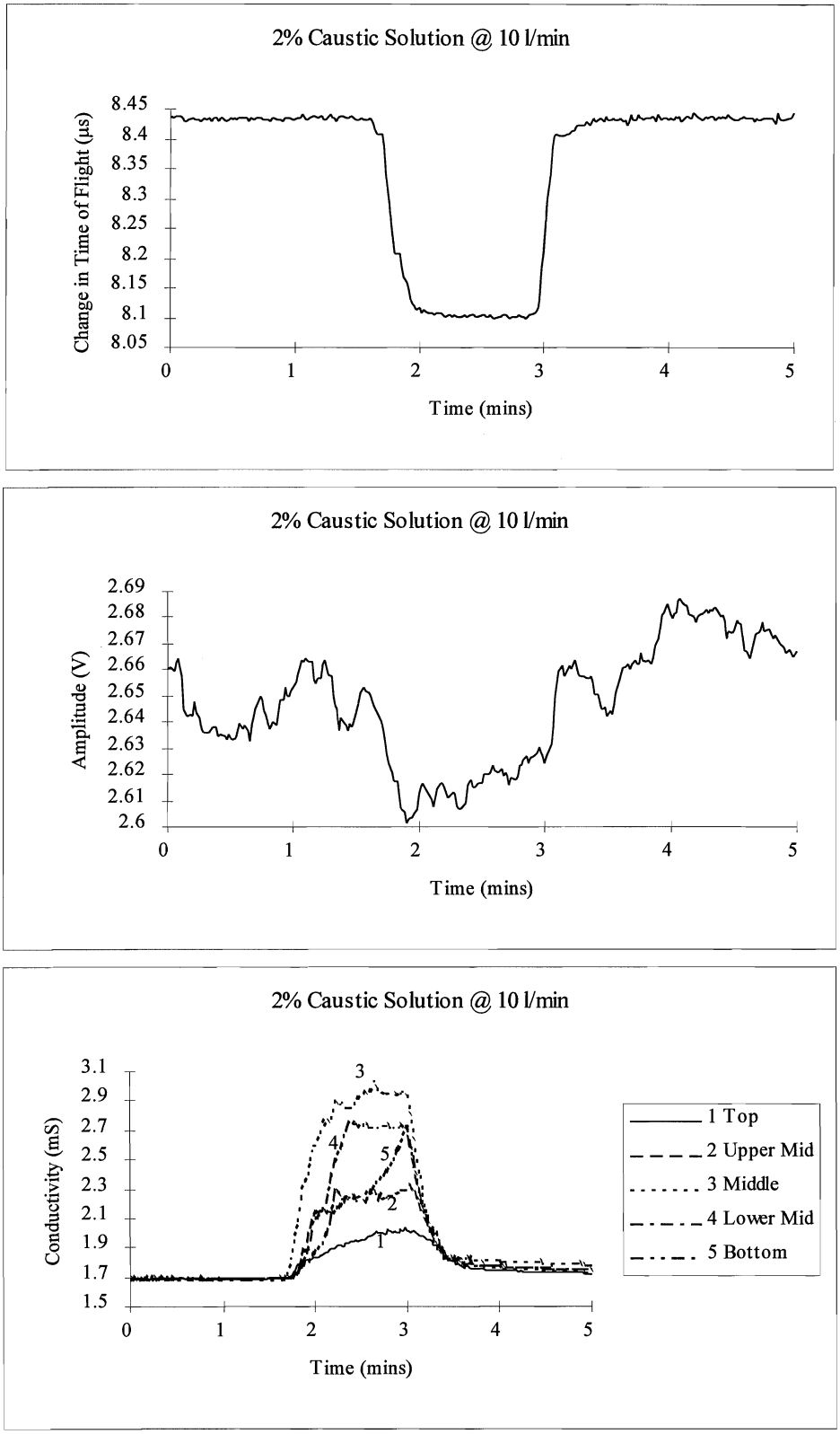
Graph 13: 50% Glucose Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



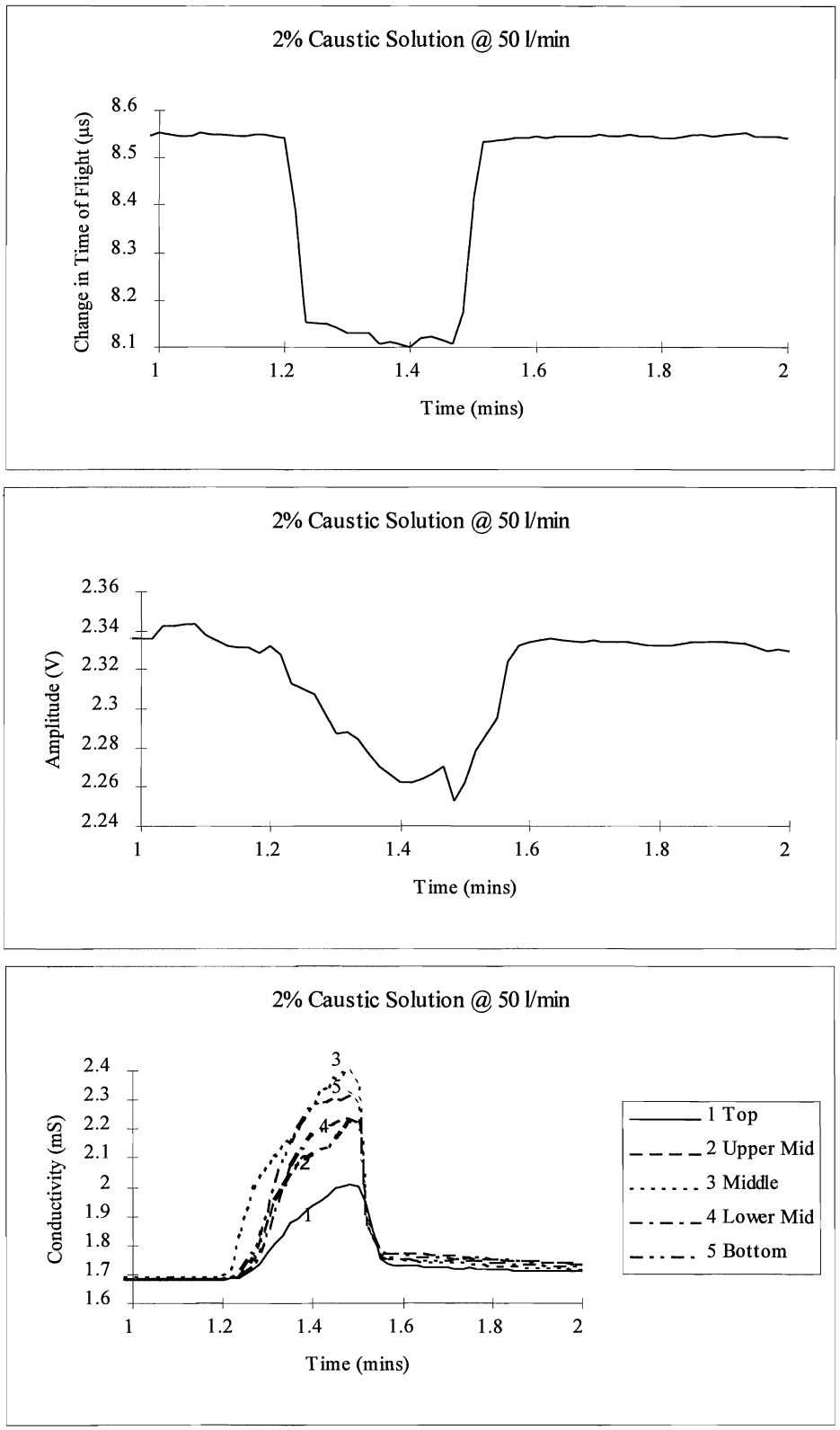
Graph 14: 50% Glucose Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



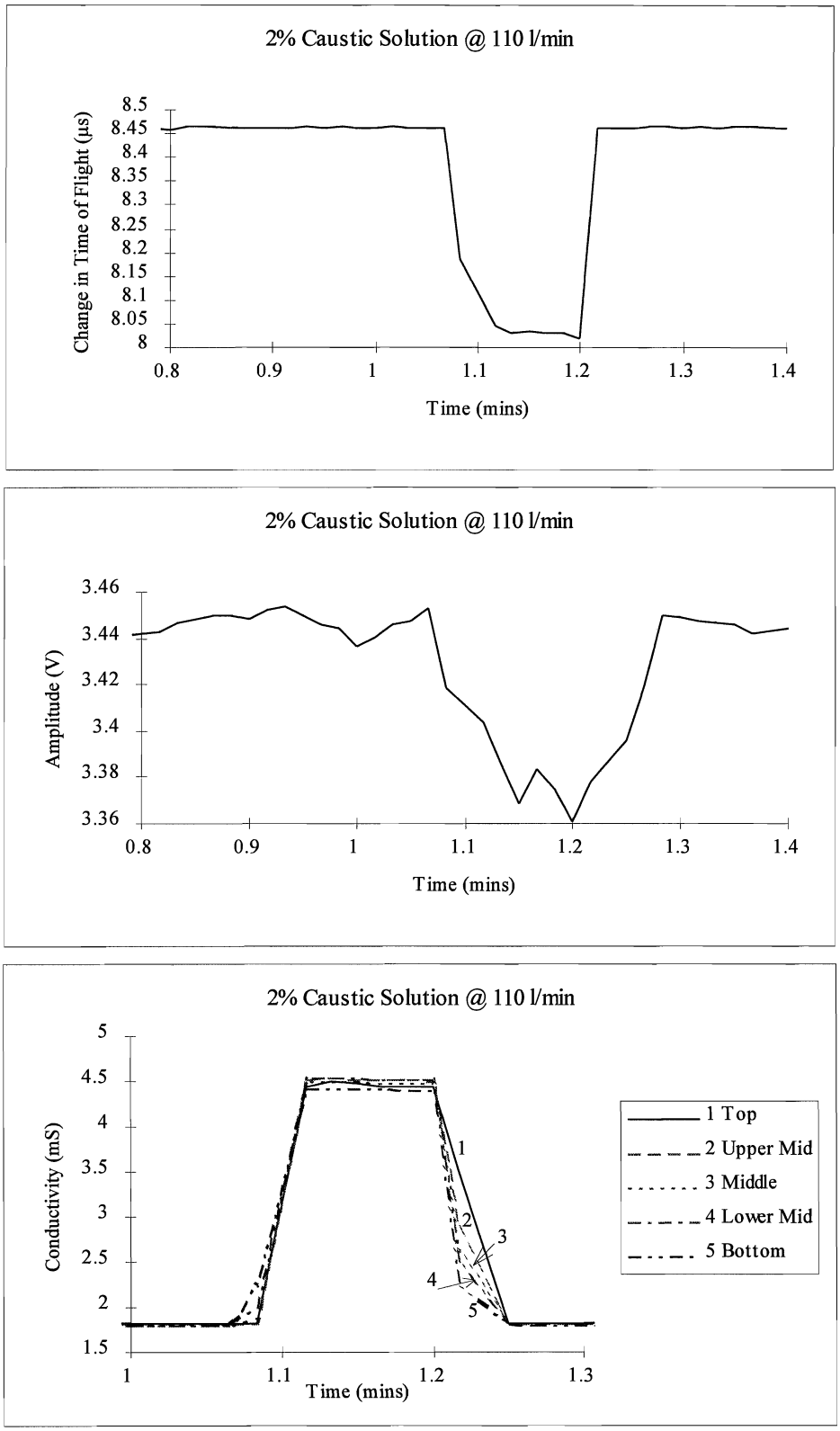
Graph 15: 2% Caustic Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



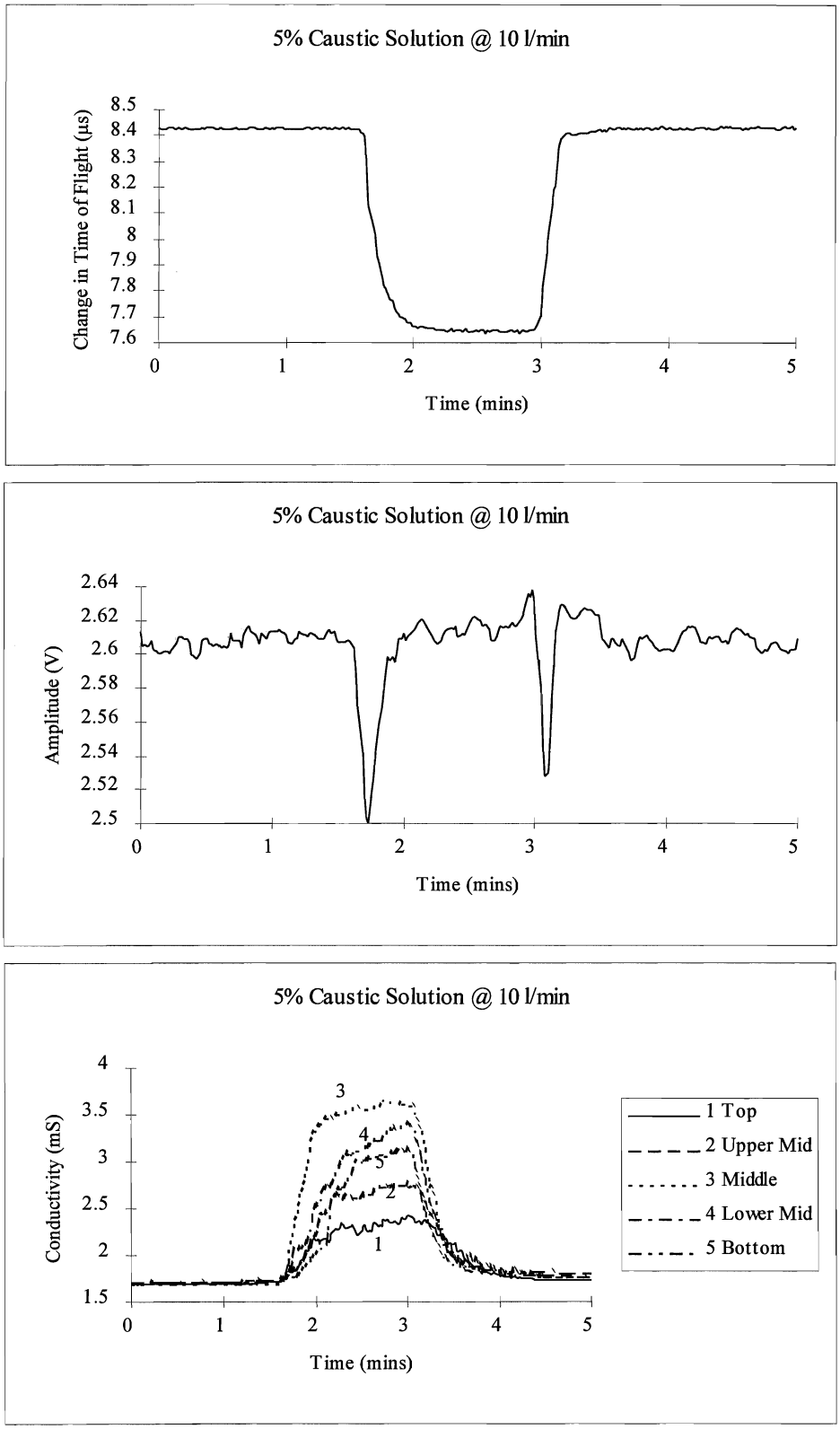
Graph 16: 2% Caustic Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



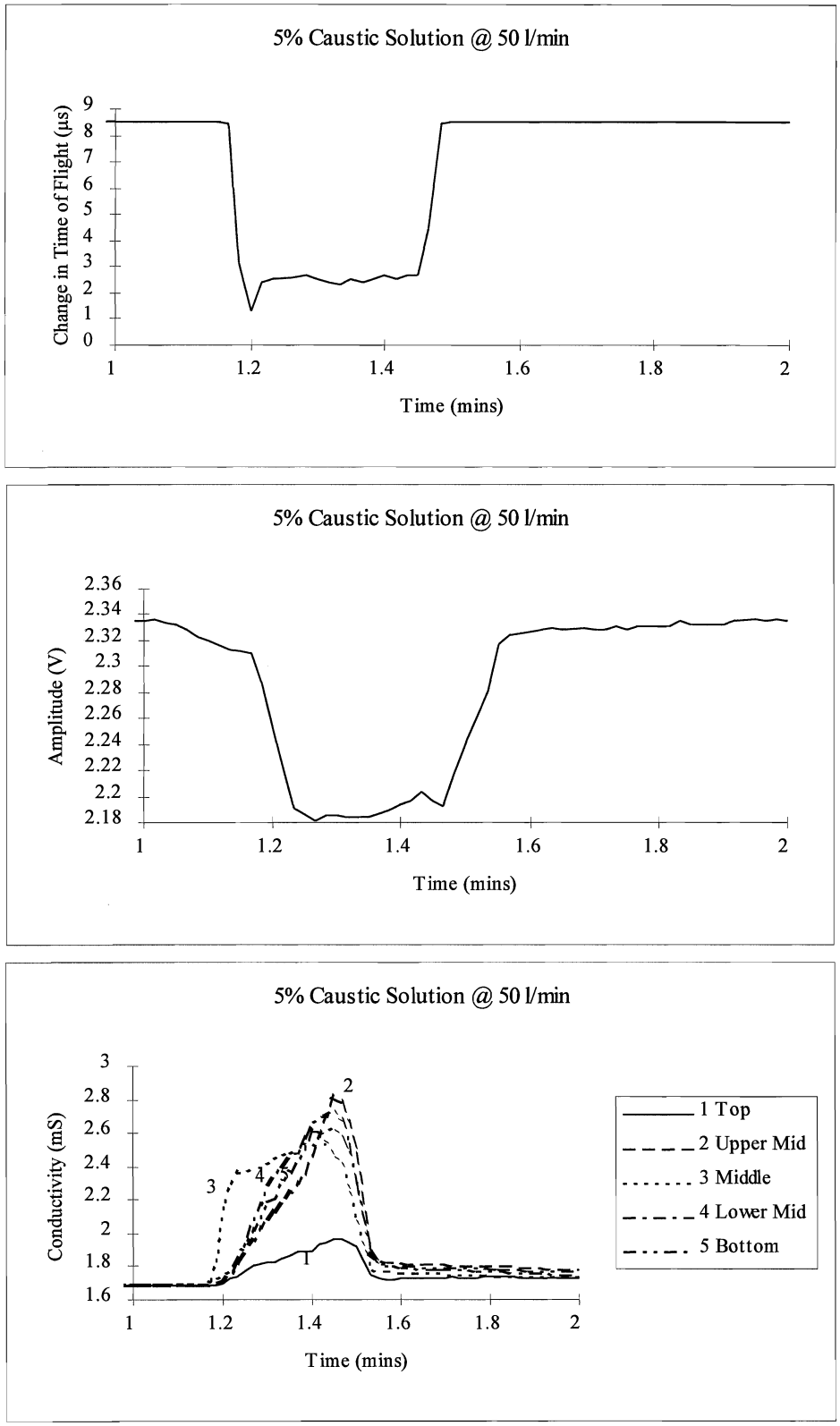
Graph 17: 2% Caustic Solution at 110 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



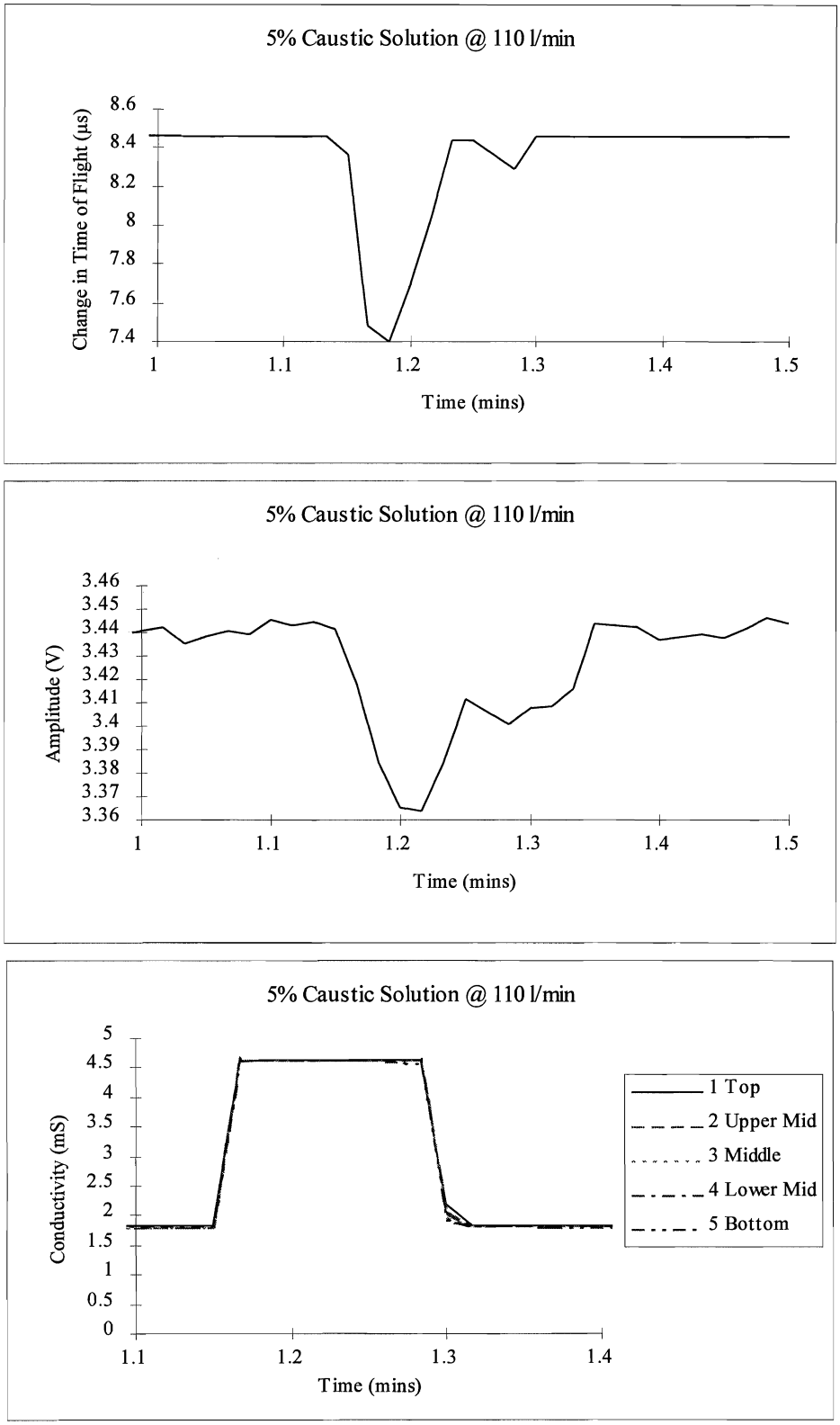
Graph 18: 5% Caustic Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor

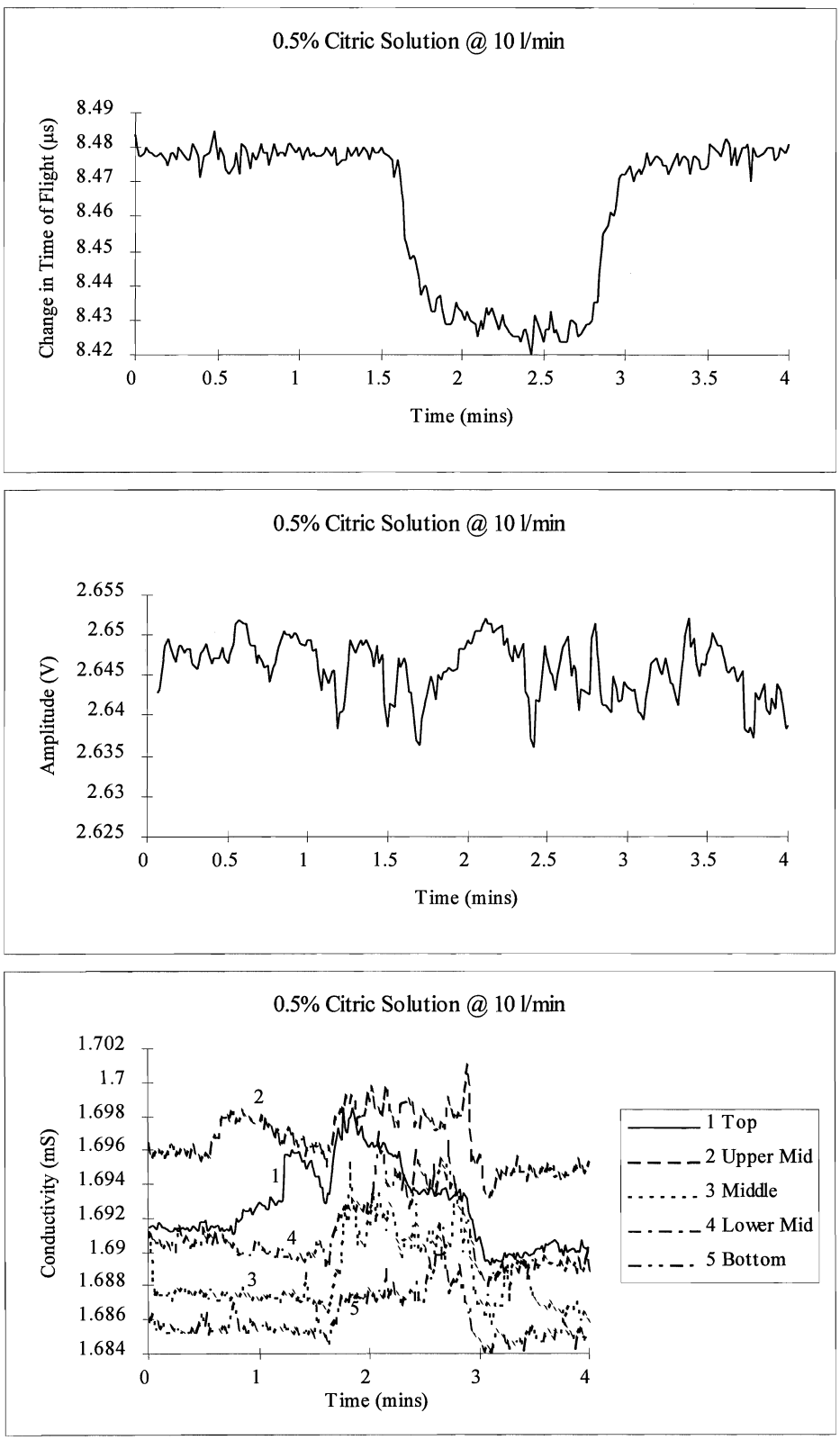


Graph 19: 5% Caustic Solution at 50 Litres/min

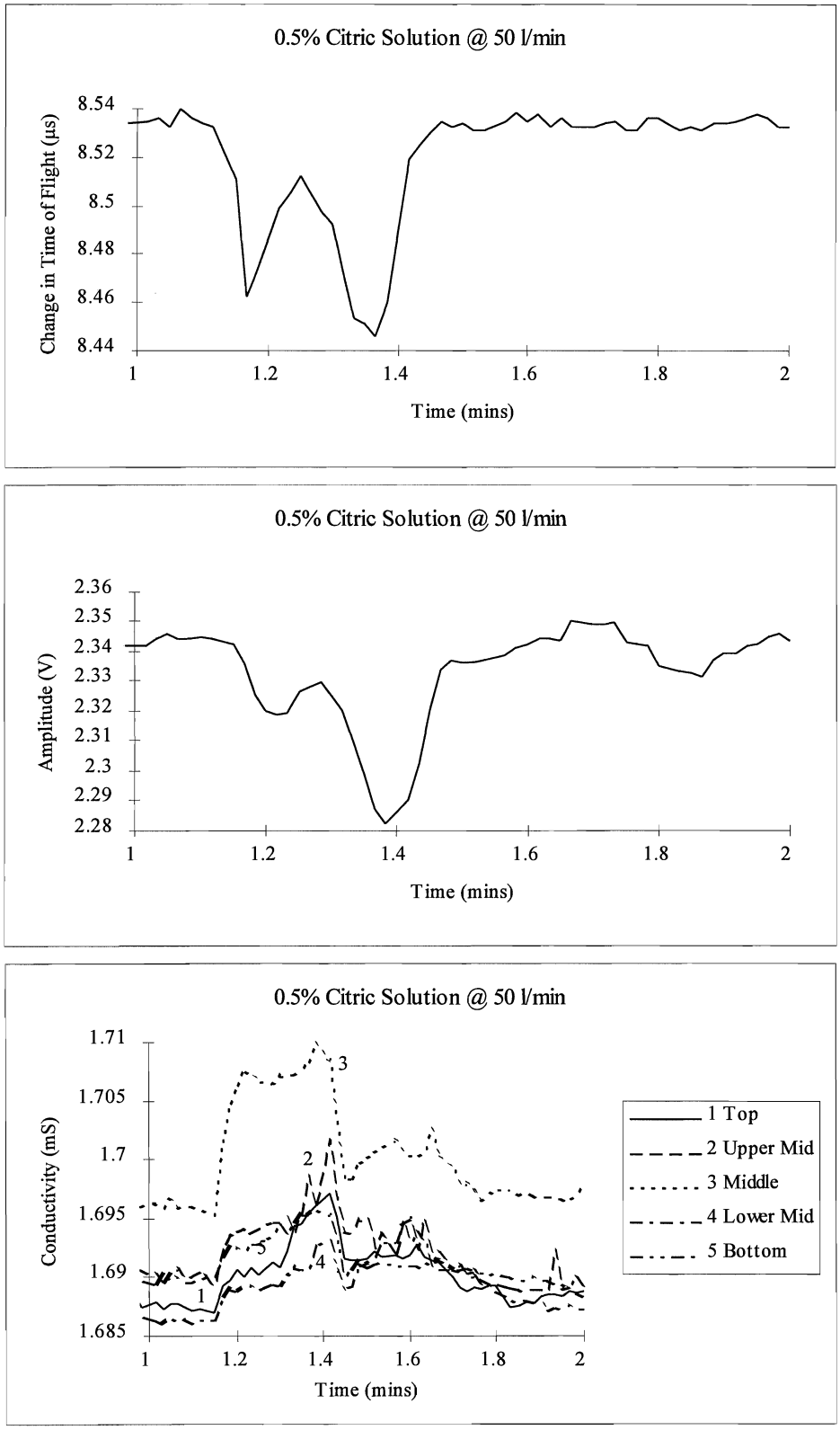
Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



Graph 20: 5% Caustic Solution at 110 Litres/min
Upper two graphs from ultrasonic sensor, lower graph from conductance sensor

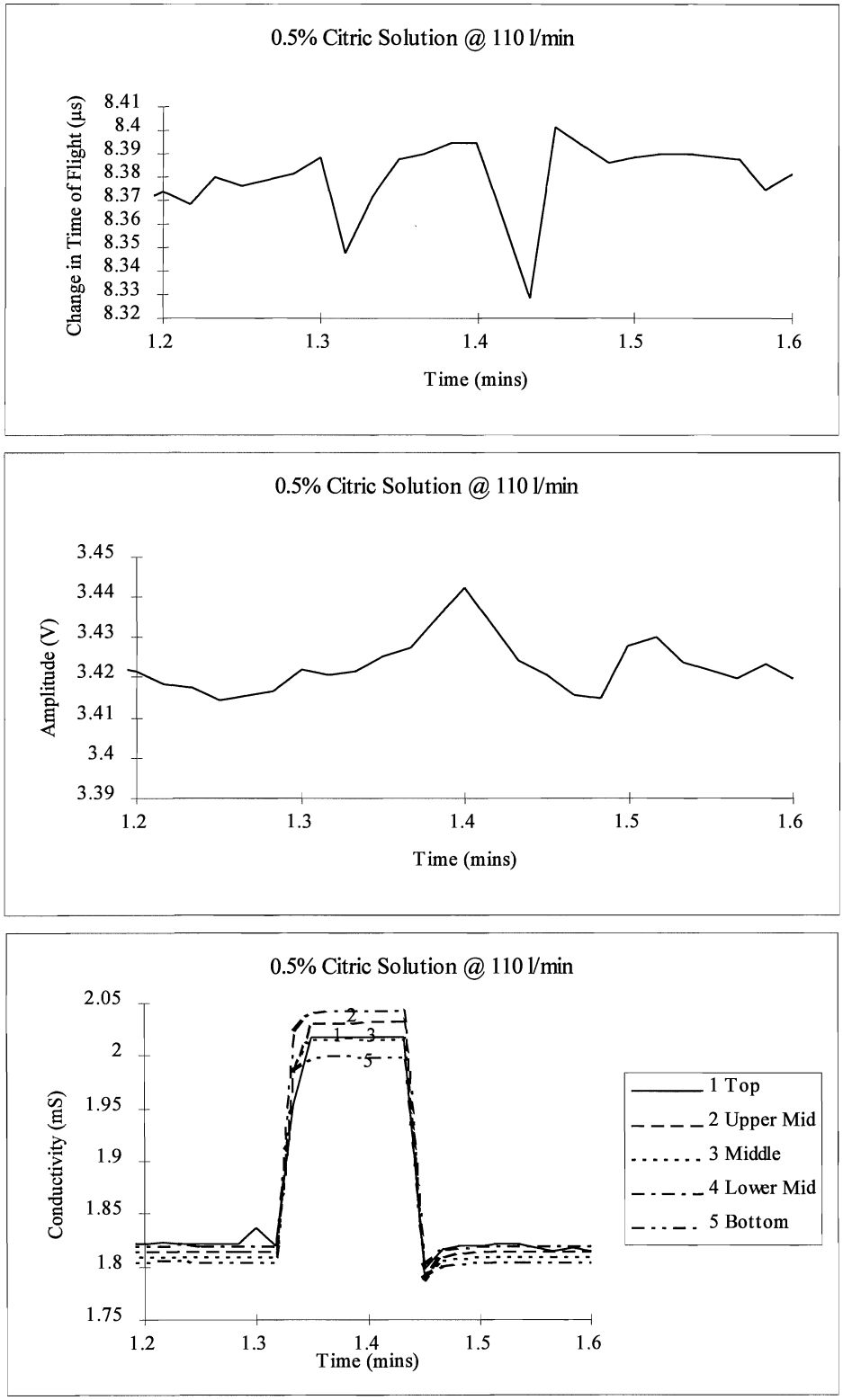


Graph 21: 0.5% Citric Acid Solution at 10 Litres/min
Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



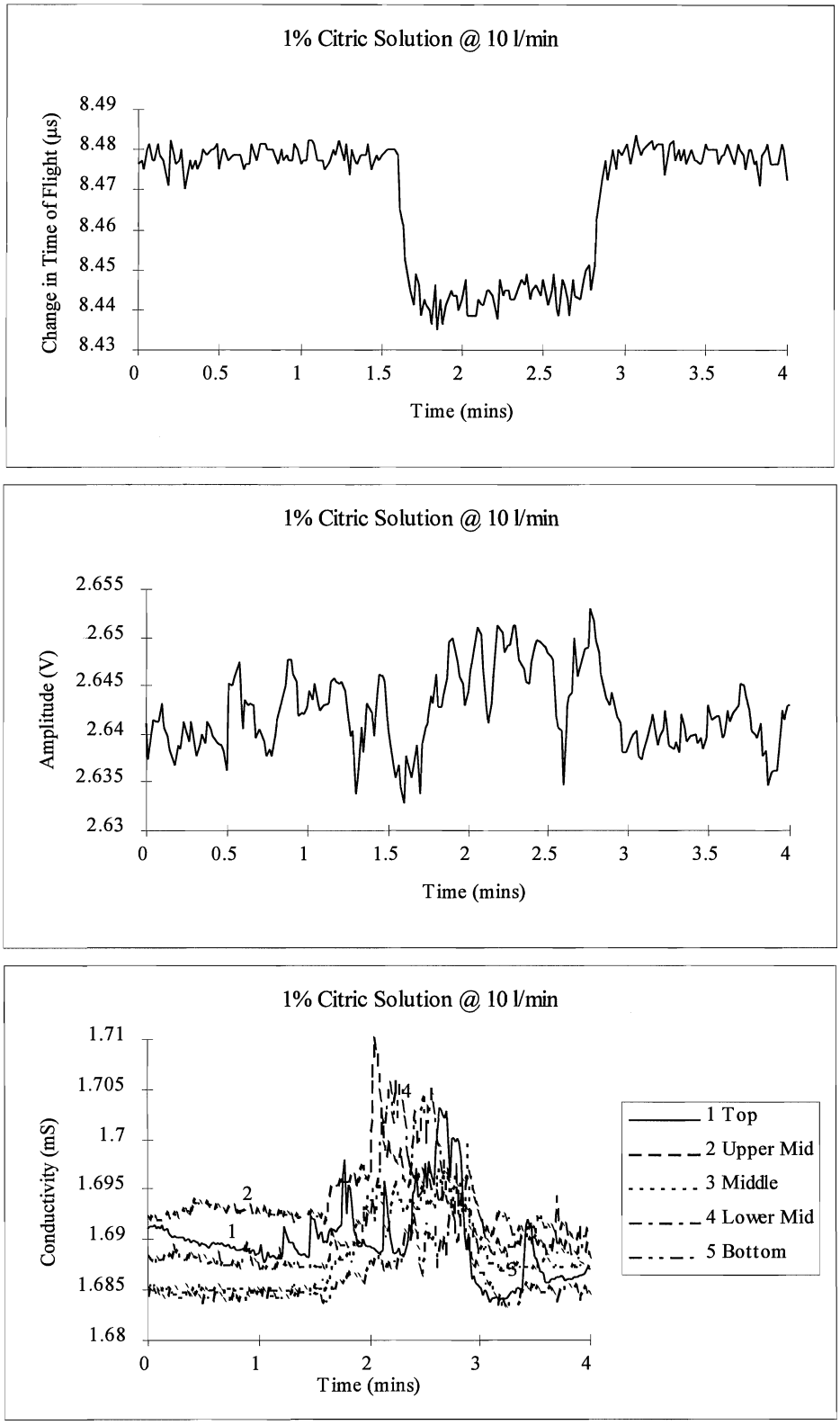
Graph 22: 0.5% Citric Acid Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



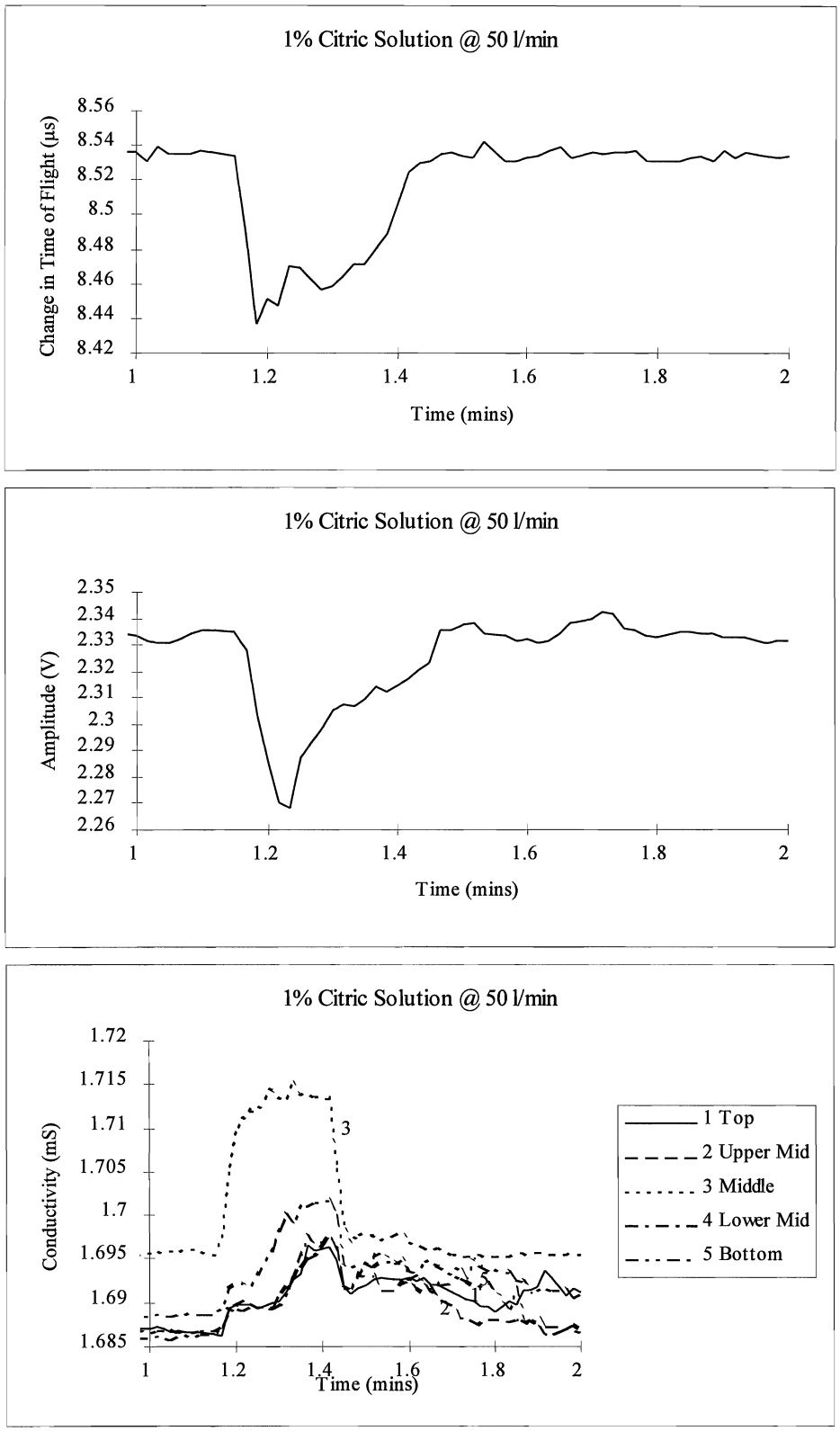
Graph 23: 0.5% Citric Acid Solution at 110 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



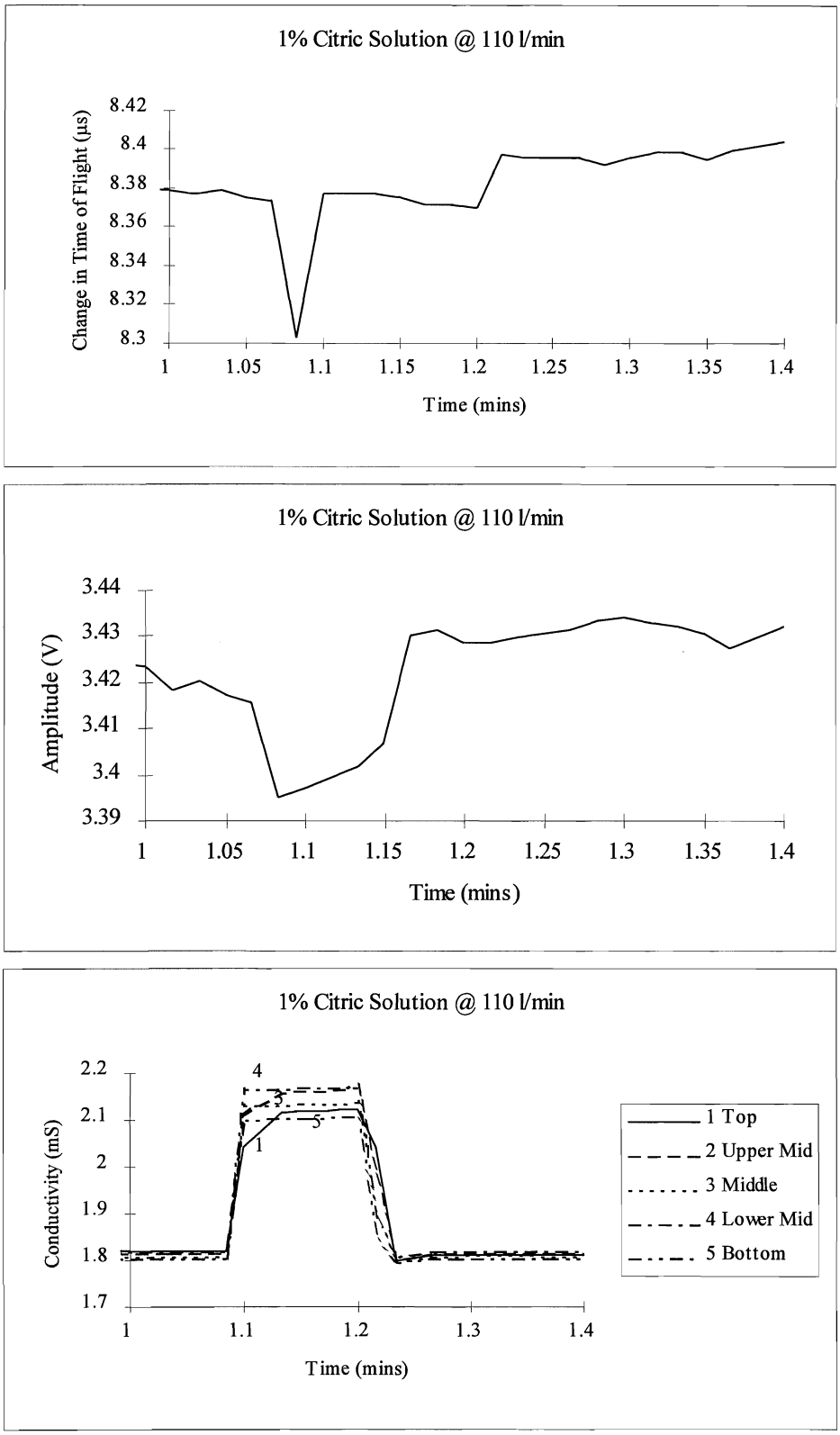
Graph 24: 1% Citric Acid Solution at 10 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



Graph 25: 1% Citric Acid Solution at 50 Litres/min

Upper two graphs from ultrasonic sensor, lower graph from conductance sensor



Graph 26: 1% Citric Acid Solution at 110 Litres/min
Upper two graphs from ultrasonic sensor, lower graph from conductance sensor