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# Paper 1.2

# Capacitive Ultrasonic Transducers for Gas Flow Metering Applications

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# CAPACITIVE ULTRASONIC TRANSDUCERS FOR GAS FLOW METERING APPLICATIONS

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## 1 INTRODUCTION

There are various types of flowmeter used in gas flow measurements, including differential pressure meters [1], turbine meters [2-3], and positive displacement meters [4]. These common flowmeters are all well characterized and readily available. However, they may cause an unsatisfactory obstruction to the gas flow and an associated pressure drop in the system. Ultrasonic flowmeters [5] are another type of flowmeter that use the interaction of acoustic waves with the moving fluid to measure the fluid flowrate. Ultrasonic flowmeters have many advantages over traditional techniques: they offer little or no obstruction to fluid flow, have a fast response, and may produce a negligible pressure drop in the system. There are three basic ultrasonic techniques. The first operates using Doppler shift [5] and hence relies on the frequency variations between the transmitted and received signals. The second uses cross-correlation to provide an estimate of the time for a particular disturbance in the flow to travel between two ultrasonic beams a known distance apart [6-7]. The third technique makes use of the ultrasonic time-of-flight between transducers using paths upstream and downstream in the fluid flow and such devices are known as transit time ultrasonic flowmeters [5,8].

Ultrasonic flowmeters in general can be used either as clamp-on or wetted [6,9], where sensors are fitted inside the pipe in contact with the fluid, but do not intrude significantly into the flow path. This usually provides increased acoustic signal strength, because no signal attenuation occurs through the pipe wall. Piezoelectric transducers are available for use in gas flowmeters under different conditions [10,12] but there is usually a large mismatch between the acoustic impedance of piezoelectric materials and that of gases. This means that they are not very efficient and the use of impedance matched layers is necessary, which has been successfully implemented and showed good results [13]. However the bandwidth of such devices is usually limited and the matching layers may be difficult to manufacture.

An alternative is the capacitive ultrasonic transducer (CUT) [14-15] which is more suitable for generating and receiving ultrasonic waves in gases, where the vibrating transducer surface is a very thin membrane with an impedance more closely matched to that of air and other gases. By exploiting the advantages of these devices in fluid flow measurement, capacitive ultrasonic transducers have been successfully applied to gas flow measurement [16][21].

The objectives of this work are to investigate the application of high frequency capacitive transducers in transit time ultrasonic flowmeters for measuring gas flowrates in different meter configurations using the same set of ultrasonic transducers for time-of-flight and frequency analysis.

## 2 CAPACITIVE TRANSDUCERS

The capacitive ultrasonic transducer in its simplest form is shown schematically in Figure 1. The devices used in this work had 9mm diameter apertures and consisted of a 5μm thick metallized Mylar flexible dielectric membrane and a rigid brass conducting backplate, forming the two electrodes of a capacitor. When a d.c. bias voltage is applied, a charge builds up between the two electrodes. When the device is acting as an ultrasonic transmitter, any transient voltage varies the charge between the electrodes and causes the membrane to move, generating an ultrasound wave. Similarly, when the device acts as a receiver, ultrasound striking the membrane causes it to move and the charge between it and the backplate electrode varies, which can be detected by a suitable charge-sensitive amplifier.

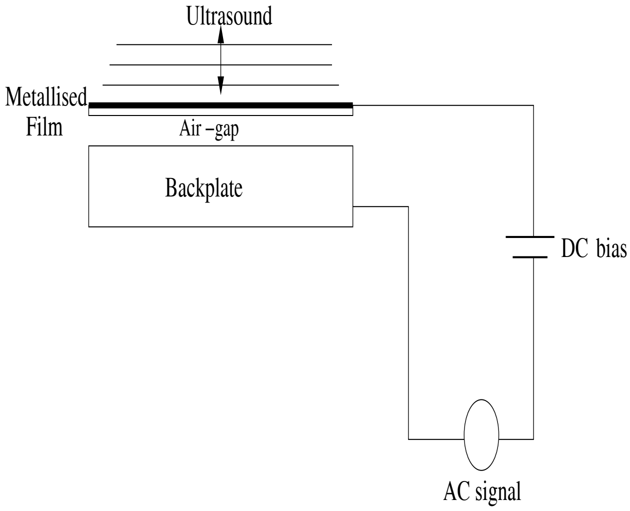


**Fig. 1 – A typical capacitive transducer**

The devices are capable of generating and receiving signals at frequencies of over 1MHz [15]. The thickness of the dielectric membrane, its material, and the surface features on the backplate electrode all combine to determine the frequency response and sensitivity of the capacitive transducer [17-18]. Figure 2(a) shows a typical waveform obtained through 30mm of air between a pair of these transducers and Figure 2(b) shows the frequency spectrum. The signal is well damped at a center frequency of 254kHz with a -6dB bandwidth of 205kHz, which is sufficient for this study.

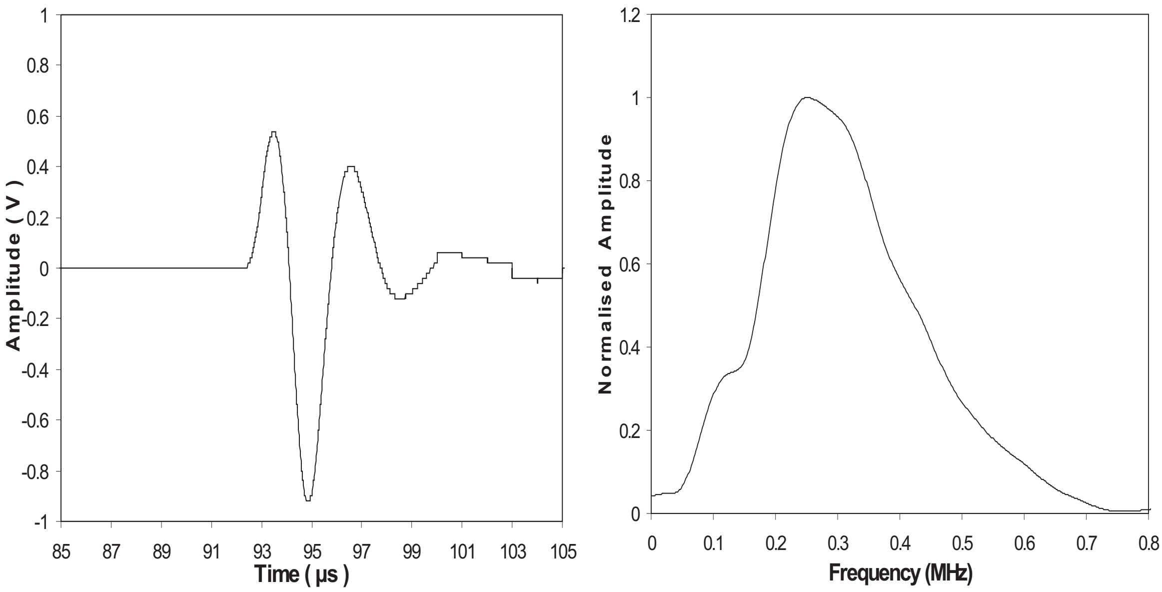


**Fig. 2 – (a) Sample waveform in air from a pair of capacitive transducers; (b) the corresponding frequency spectrum.**

## 3 PRINCIPLE OF MEASUREMENT

The measurement principle of the transit time ultrasonic flowmeters is based on the difference between the transit times of ultrasonic signals emitted over one or more propagation paths upstream and downstream in the moving fluid. The differences between the transit times of the signals are proportional to the fluid velocity. It is usually easier to determine the difference between upstream and downstream times accurately if this difference is made as large as possible, which can be done by increasing the ultrasonic path length by allowing one or more reflections from wall to wall within the pipe. Since the transit time is proportional to the pipe diameter, small measurements in small pipes are usually achieved by transmission of the ultrasonic beam axially along the pipe [6] or by using single or multiple reflections along the pipe. Figure 3 shows the single ('V') and multiple ('V+1' and 'W') reflection configurations used in this work.

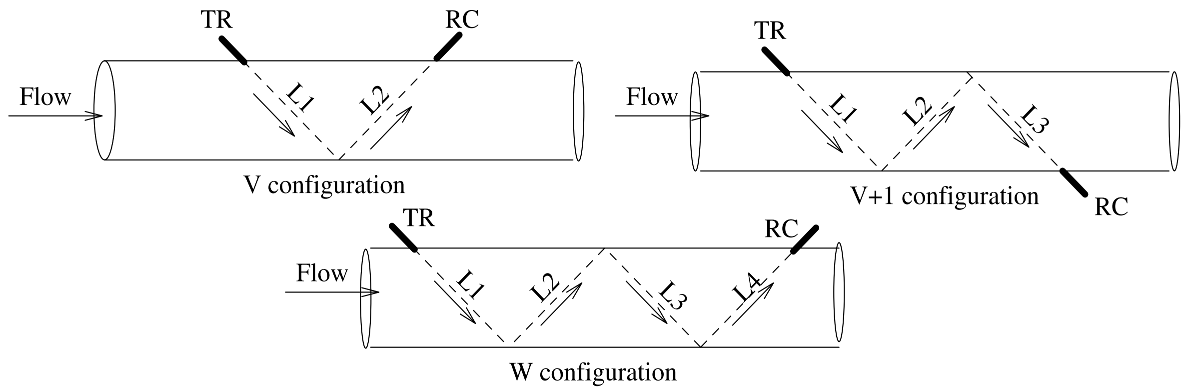


**Fig. 3 - Ultrasonic transducer configurations in the meter section.**

The fluid velocity $v$ along an ultrasonic path $L$ in a pipe at angle $\theta$ to the flow direction is given by [6,8]:

$$v = \frac{L}{2\cos\theta}\frac{\Delta t}{t_u t_d} \tag{1}$$

where $t_u$ is the time of flight in seconds for the upstream path, $t_d$ is the time of flight in seconds for the downstream path, $\Delta t$ is the difference between $t_u$ and $t_d$ and $L$ is the ultrasonic path length in meters between the transmitter and receiver. The total path length $L$ ( $= L_1 + L_2 + \ldots + L_n$) can be expressed in terms of the internal diameter $d$ of the pipe by $L = d/\sin\theta$. For the three meter configurations ('V', 'V+1' and 'W') used in this study, $L = 2d/\sin\theta$, $L = 3d/\sin\theta$ and $L = 4d/\sin\theta$ respectively. The mean fluid flow velocity $v_m$ in the pipeline is related to the measured velocity $v$ along the ultrasonic path by a meter factor $k$ given by [5-6]:

$$k = \frac{v}{v_m} \tag{2}$$

The mean pipe velocity $v_m$ is then simply multiplied by the pipe cross sectional area $A$ to extract the volumetric flowrate $Q$.

$$Q = v_m A \tag{3}$$

## 4 EXPERIMENTAL APPARATUS

The experiimental rig shown in Figure 4 was used to investigate the ultrasonic gas flowmeter using CUTs. The rig was constructed from 26.6mm internal diameter smooth PVC pipe, and interchangeable meter sections consisting of twin-path single-reflection ('V') and twin-path multi-reflection ('V+1' and 'W') configuration spool piece arrangements were manufactured as shown previously in Figure 3. The capacitive ultrasonic transducers (CUTs) could not act as transmitter and receiver at the same time due to limitations of the available electronics, hence two transducer pairs were needed to achieve upstream and downstream paths. The transducer ports were on opposite sides of the pipe as shown, and the upstream and downstream paths were offset along the pipe circumference to prevent turbulence and vortices shed from the ports from affecting any transducers downstream. The flowmeter consisted of two pairs of capacitive ultrasonic transducers with 9mm apertures to generate and receive ultrasound. A calibrated

Platon gas flowmeter and regulating valve for a compressed air supply were used to produce flows of up to 100 litres/minute in the meter section. This supply was set up 20 diameters upstream of the meter section and the downstream distance to the pipe exit also was 20 diameters to ensure a fully developed flow profile in the meter section. The transmitters were driven by an AVTECH AVRH-1-C pulse generator at 200V and 2µs pulse width. The receivers were attached to a Cooknell CA6/C charge amplifier with SU2/C power supply with a charge sensitivity of 250mV/pC. The output signals from the amplifier were then captured and displayed on a Tektronix TDS 210 digital oscilloscope with bandwidth of 60 MHz before being transferred to a PC via a GPIB (General Purpose Interface Bus) interface for storage and analysis. A LabVIEW program was written in order to control the data acquisition and perform the analysis and calculate the flowrates. A threshold peak detector function was used to determine the times of flight of the ultrasonic waves upstream and downstream at different flowrates, using a percentage of the maximum signal height as the threshold value that could be adjusted as required.

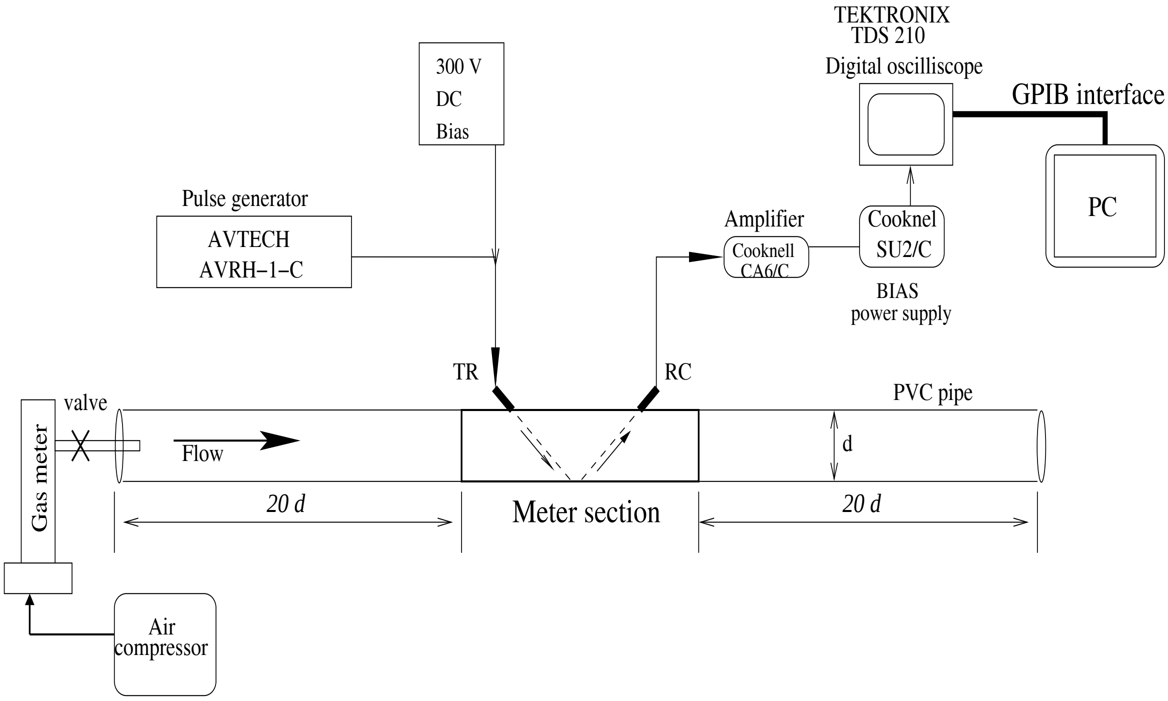


**Fig. 4 - Experimental apparatus for the measurements.**

The ultrasonic path length *L* in the upstream and downstream directions could be calculated precisely from the calibration process for each flowmeter at the initialisation setting. This process involved evaluating the air temperature and pressure and calculating the speed of sound in air under these conditions. Then, the times-of-arrival of the upstream and downstream signals were measured using the threshold technique, which were equal at zero flow and used to accurately determine *L*. The positions of the transducers in the ports could be adjusted to equalize the upstream and downstream path lengths.

## 5 RESULTS AND DISCUSSION

### 5.1 Time-of-flight data

The flowrate in the test pipe was measured using the ultrasonic system at flowrates up to 100 litres/minute. The flow regime in the meter sections for this range of flowrates varied from laminar flow through transitional flow to turbulent flow, given the Reynolds number values as shown in Table 1.

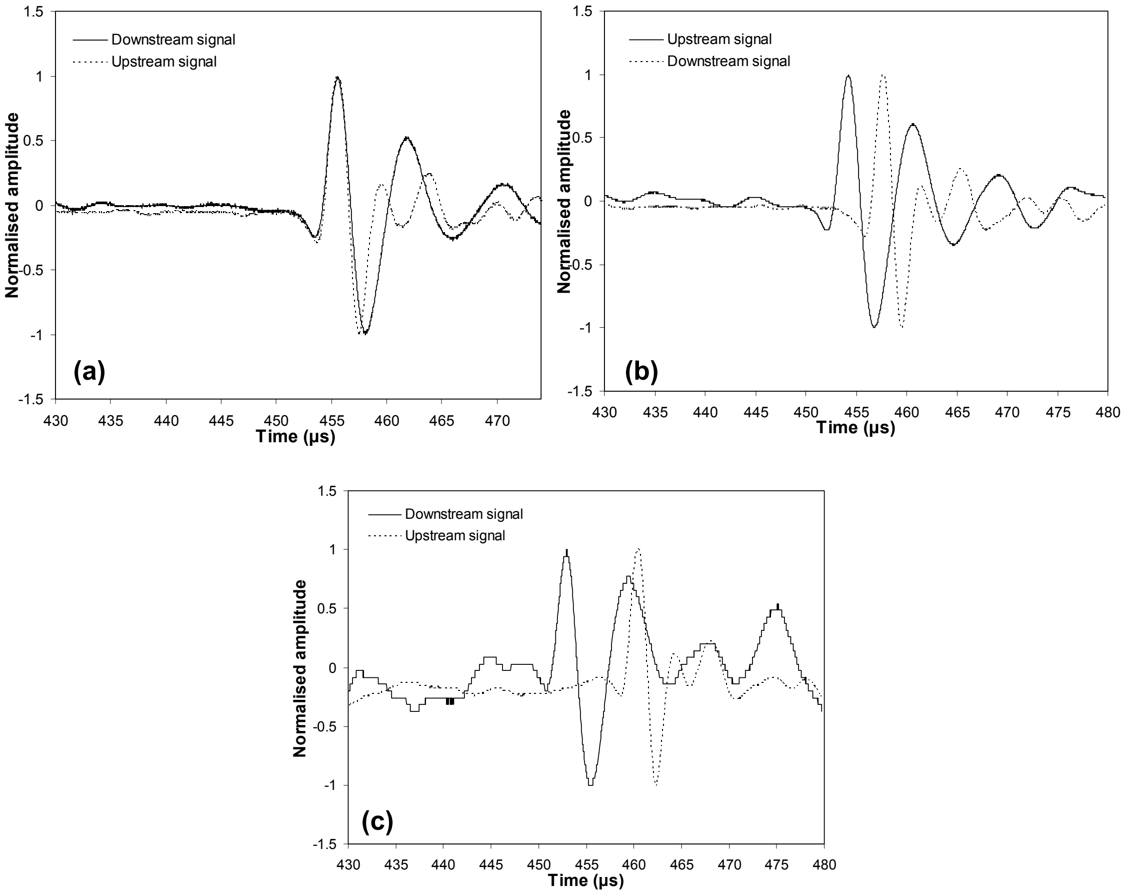


**Fig. 5 - Ultrasonic signals at (a) 0 litres/min, (b) 50 litres/min and (c) 100 litres/min.**

Ultrasonic waveforms from the upstream and downstream paths at different flowrates and different configurations were obtained for analysis. Typical upstream and downstream waveforms from the 'W' configuration are shown in Figure 5, with (a) a signal obtained with no flow in the meter section, and the changes in propagation times produced by (b) flowrates of 50 litres/minute, and (c) 100 litres/minute. Similar waveforms were obtained from the ‘V’ and 'V+1' meter configurations, with the ‘V+1’ signals inverted due to the odd number of reflections within the pipe. The time shift between the upstream and downstream signals was determined at different flowrates using the threshold peak detector technique for the different section configurations.

**Table 1 - Flow regimes inside the meter section.**

| **Gas flow** (litres/min) | **Flow velocity** (m/s) | **Reynold's number ($R_e$)** | **Flow regime** |
|---|---|---|---|
| 20 | 0.6 | 1245.5 | **Laminar** |
| 30 | 0.9 | 1868.3 | **Re < 2000** |
| 40 | 1.2 | 2491 | **Transitional** |
| 50 | 1.5 | 3113.8 | **2000 < Re > 4000** |
| 60 | 1.8 | 3736.5 | |
| 70 | 2.1 | 4359.3 | **Turbulent** |
| 80 | 2.4 | 4982 | **Re > 4000** |
| 90 | 2.7 | 5604.8 | |
| 100 | 3.0 | 6227.6 | |

The measured flowrates using the ultrasonic system for each meter configuration were plotted against actual flowrates as shown in Figure 6. The ultrasonic measurements agreed well with the actual flows and linear correlations were fitted to all three configurations. The meter factor *k,* correcting the ultrasonic flow measurements to the actual flowrates, was calculated for each meter configuration, and found to be 0.90, 0.910, and 0.911 with $R^2$ values of 0.997, 0.996 and 0.998 for the 'V', 'V+1' and 'W' configurations respectively. Thus, the 'W' flowmeter produced a more accurate flow measurement as expected due to the longer ultrasonic path.

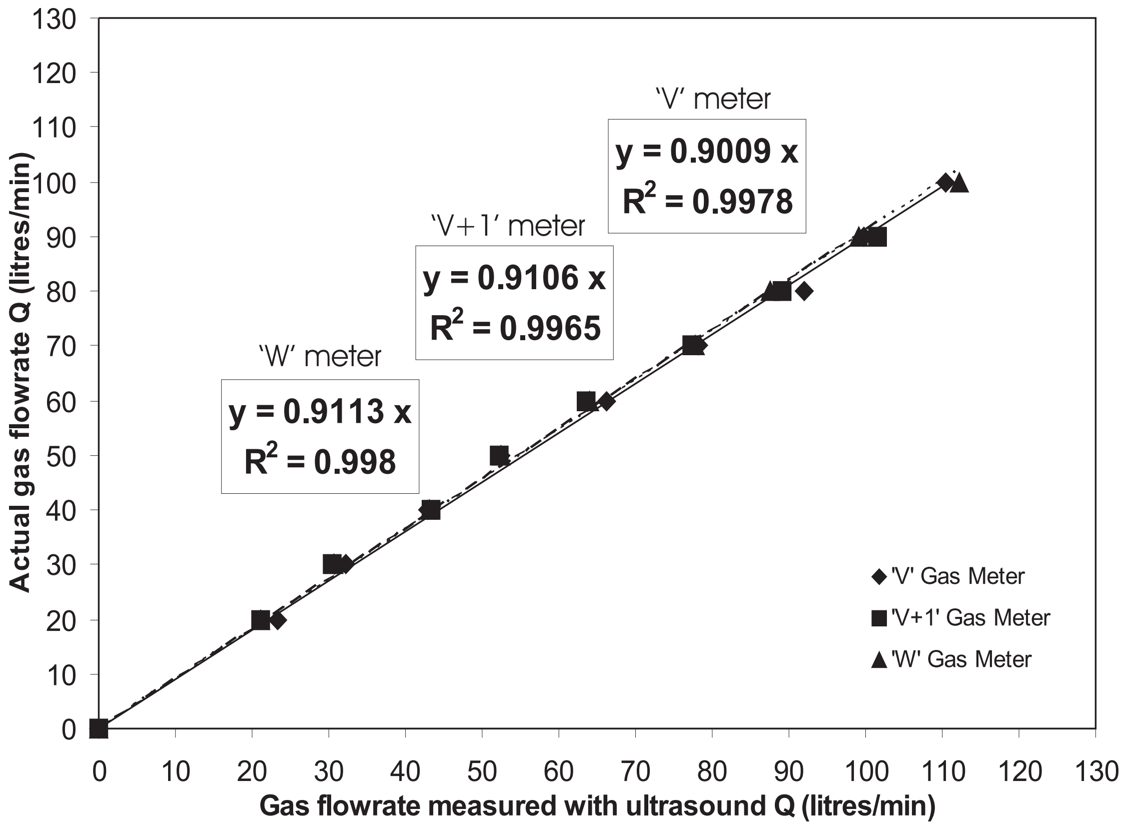


**Fig. 6 - Measured flowrate against actual flowrate for 'V','V+1'and 'W' meter configurations.**

## 5.2 Frequency and amplitude data

A frequency analysis for the ultrasonic upstream and downstream signals for the three meter configurations was also carried out. A flow-dependent frequency shift was observed in ultrasonic measurements simultaneously with the transit time signals. A flow-dependent amplitude change was also observed in the upstream and downstream signals. Frequency spectra of the received ultrasonic signals from the upstream path [Figure 7(a)] of the 'W' meter at various flowrates from 0 to 100 litres/minute were calculated, with normalised spectra shown in Figure 7(b). The attenuation of the ultrasonic waveforms is increasing with an increase in gas flowrate and also the centre frequency of the ultrasonic waveforms is shifted for both the upstream and downstream signals. The change in amplitude and increase in the attenuation of ultrasonic signals will be caused by a number of factors, including turbulence of the gas in the meter section, which was highest at flow of 100 litres/minute. The attenuation of ultrasonic waves in gases is also affected by several gas characteristics such as density and shear viscosity [19,21] which are already accounted for in Reynolds number [3,6]. The increase in signal attenuation may also contribute to the decrease in the centre frequency as ultrasonic attenuation is heavily frequency dependent [19,21]. The ultrasound will also be Doppler shifted as it is scattered from eddies, vortices and other disturbances in the gas flow. The ultrasonic beams also diverge, and more energy will be diverted away from the direct path to the receivers as the flow rate increases.

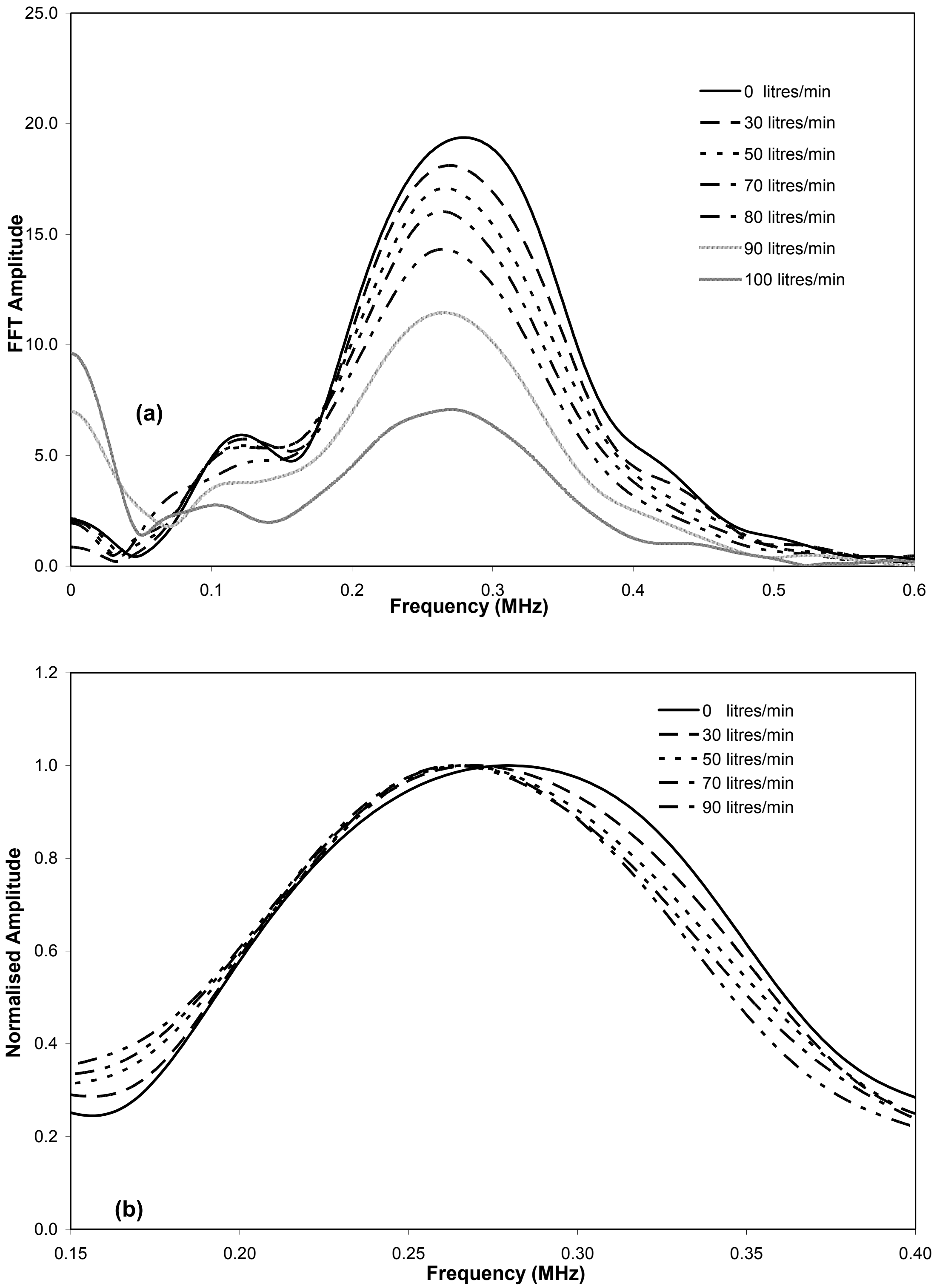


**Fig. 7 – Typical plots of (a) decreasing amplitude and (b) shift in centre frequency with gas flowrate for the upstream path in the "W" meter configuration.**

The amplitude data for the upstream signals in the 'W' meter was plotted against the flowrate in Figure 8(a) with a linear trend up to about 70 litres/minute when the flow becomes turbulent with a Reynolds number of 4359.30, and a non-linear/polynomial (cubic equation) with $R^2$ = 0993 was fitted to all the data. The centre frequency data for the upstream signals was also plotted against gas flowrate as shown in Figure 8(b) for the 'W' meter along with the curve of 3rd-order polynomial fitting with $R^2$ = 0.992. However, as the range of flows in the meter section varies

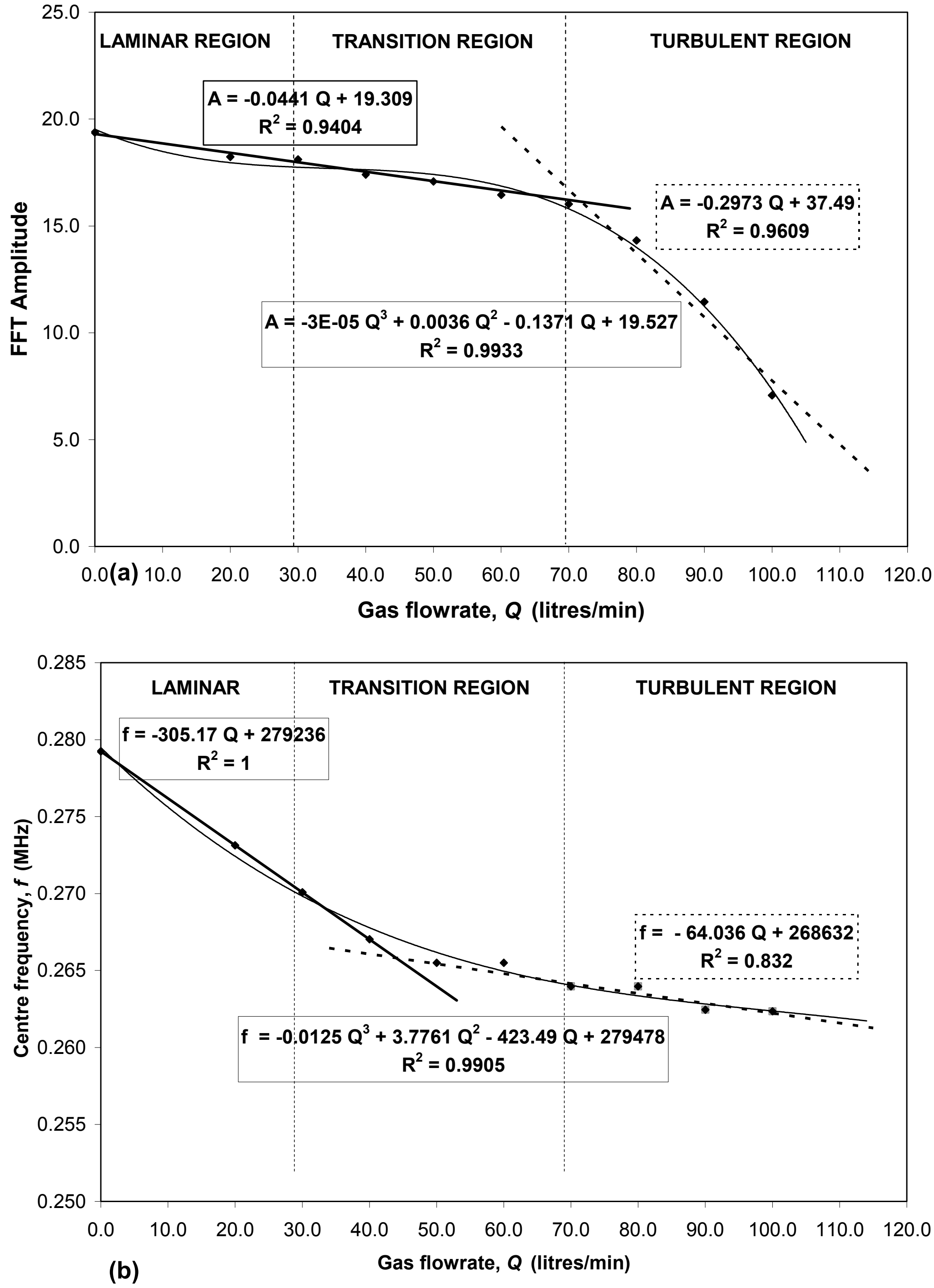


**Fig. 8 – (a) decreasing amplitude and (b) shift in centre frequency with gas flowrate in the "W" configuration meter.**

from laminar, transitional and turbulent, it can not be clearly ascertained that a single relationship is valid, and there may be separate trends in the laminar and turbulent regions. For the "W" meter, the amplitude data in Figure 8(a) was also fitted with linear trends in the laminar and turbulent regions with $R^2$ values of 0.940 and 0.960 respectively. The data of the flow-dependent frequency shift in Figure 8(b) was also fitted with separate linear trends for the laminar and turbulent regions with $R^2$ values of 1.0 and 0.832 respectively. Hence, it is possible to determine the flowrate using only a single ultrasonic path, by monitoring the frequency shift or amplitude change of the received signals irrespective of the flow regime in the pipe, resulting in a simplified flowmeter.

## 6 CONCLUSIONS

In this work, the use of capacitive ultrasonic transducers CUTs for gas flowmeters has been investigated. Three different meter configurations were used with a different number of reflected paths (‘V’, ‘V+1’ and ‘W’). The determination of gas flowrates up to 100 liters/min was achieved with a high degree of accuracy, this demonstrates the suitability of capacitive ultrasonic transducers for gas metering applications. The work also shows that a frequency shift is flowrate dependent, which can be calculated simultaneously with any transit-time technique may also be used to determine the flow rate using a single ultrasonic path. Future work will investigate CUTs for flow metering at elevated pressures, elevated temperatures, and in pipe geometries with turbulent flow only.

## 7 ACKNOWLEDGEMENTS

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