CHARACTERISATION OF CAPACITIVE ULTRASONIC TRANSDUCER GAS FLOW METERS

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ABSTRACT

Many manufacturing processes rely on accurate flow metering, and ultrasonic flow meters are well established in this area. Most ultrasonic flow meters use piezoelectric transducers which are not very efficient at generating ultrasound in gases, and tend to be highly resonant which then limits their application. Capacitive ultrasonic transducers are an alternative device technology that can generate and detect ultrasound very efficiently in air and other gases, and produce transducers that are inherently broadband, meaning that additional frequency information may then be utilised.

Of critical importance is the meter correction factor *k*, which correlates the ultrasonically measured flow rate with the actual flow rate in the metering section. Most flow meters require at least 15 diameters of straight pipe upstream and 5 diameters downstream, to allow the flow profile to become fully developed before it enters the metering section. This means that on-site calibration is usually a necessity. The *k*-factor varies depending on the specific installation of the flow meter, and also the flow regime, as it is related to the fluid flow profile. The ultrasonic measurements are typically of the average axial flow velocity along the shortest path of the ultrasonic beam. This then makes the ultrasonic measurements difficult to predict, due to (i) beam spreading as a result of diffraction, (ii) the relatively large area of the wetted transducer face, (iii) curvature of the pipe wall in multi-path meter sections, and (iv) the assumed symmetry of the flow profile.

This work has investigated the use of capacitive ultrasonic transducers in multiple reflection contrapropagating gas flow meters ("V", "Z", "W" and "VZ" transducer configurations). Air flow at rates of up to 100 litres/min at ATP through the different meter sections was modelled using COSMOSFloWorks™ for different meter configurations, and included a number of right-angled bends at various distances upstream of the meter section to produce asymmetric flow profiles. Data along multiple chords within the ultrasonic beam was extracted from the models and use to predict the *k*-factor. Measurements were then made on an experimental rig, and there was good correlation between theory and experiment.

KEYWORDS: Process monitoring; Quality Control; Ultrasound

1. INTRODUCTION

Ultrasonic flow meters are minimally invasive flow meters which send an ultrasonic pulse through the fluid flow and measure changes such as relative transit time or frequency shifts in the ultrasonic wave. Ultrasonic flow meters can be used in liquids, gases, and solid particulate matter. Flow magnitudes can range from just a few metres per second to Mach 1 and beyond in the case of gases. Conduit sizes can range from 1mm or less in medical applications to over 10m in open conduits [1]. Ultrasonic flow meters can remain effective in applications involving extreme conditions, operating effectively at temperatures from -40°C up to 250°C and at pressures of up to 100bar [2].

The main area of application for ultrasonic flow meters is in the process industry, where there is a high level of automation and continuous process control. Ultrasonic flow metering has also been used extensively in energy distribution networks, particularly in the distribution of natural gas, and has several key advantages over competing technologies. Ultrasonic flow meters are minimally invasive and they avoid inertial effects and do not cause a pressure drop within pipe networks. Ultrasonic technology also provides for a high turn-down ratio as well as good accuracy and reproducibility. A fast response time is also achieved as a new ultrasonic signal is generated for every measurement cycle. Ultrasonic flow meters contain no moving parts as such, and are insensitive to dirt and abrasion, thus they require only minimal maintenance [3, 4].

Clamp-on ultrasonic flow meters are non-invasive and can be coupled to the exterior of pipe work in order to measure the velocity of the flowing medium. There are issues in terms of refraction as the ultrasonic wave passes through the pipe wall into the flowing medium, they may be interfered with, and incorrect setup and use can lead to measurement errors. However, clamp-on devices are easily transported to a site for point measurements, which do not require the same accuracy as critical process control instrumentation in a process plant [4]. In such devices the dominant source of error is usually uncertainty in the flow profile, but in conduits of small diameter or where the pipe wall thickness is excessive, other errors predominate [5].

Wetted ultrasonic flow meters, used in this work, avoid the effects of refraction as the transducer is immersed directly within the flowing medium. Such intrusive transducers can be installed into standard pipe fittings on a permanent basis [5]. The adoption of high precision manufacturing techniques to help ensure exact geometrical positioning of the transducers, and the application of appropriate calibration procedures, can lead to highly accurate readings of flow rate in critical process applications [6]. Ultrasonic flow meters may use Doppler shift, cross-correlation, vortex shedding, or contrapropagating transit-time methods to determine fluid flow velocity [1].

1.1. Transit-Time Ultrasonic Flow Meters

The transit-time or contrapropagating flow meter principle of operation is based on the modification of the time-of-flight of the ultrasonic pulse by the fluid flow between an upstream and downstream path. In the most basic configuration the upstream and downstream transducers are diametrically opposed at an angle θ to the axial direction of flow in the pipe. The transit times of the ultrasonic pulse and the differential between an upstream and downstream pulse are functions of the fluid velocity and so the fluid velocity v can be easily determined by the following expression [7]:

$$v = \frac{L}{2\cos\theta}\frac{\Delta t}{t_1 t_2} \tag{1}$$

where t_1 and t_2 are the times-of-flight for the upstream and downstream paths, respectively, Δt is the difference between t_1 and t_2, L is the path length and θ is the angle made with the central axis of the pipe. However, the accuracy is affected by the fluid velocity profile, which can be difficult to predict. Uncertainties can arise from the transition of the fluid flow between laminar and turbulent due to changes in average fluid velocity. Of critical importance is the meter correction factor k, which correlates the ultrasonically measured flow rate with the actual flow rate in the metering section. A different correction factor may be appropriate for the same configuration depending on the Reynolds number, and it is possible to program a “smart” flow meter to take account of this transition.

The position of the ultrasonic path will have a significant effect on the correction factor. For both laminar and turbulent flows, diametrical paths will tend to overestimate the flow rate in the metering section as the path takes maximum possible account of the central region of the flow where the velocity is greatest. Several variations of meter configuration have been developed to reduce the influence of the velocity profile by determining a mean velocity over a number of acoustic paths. Some configurations use off-centre mid-radius paths to get a mean value, with weightings being applied to the different paths depending on their positions relative to one another in the pipe. Others use multiple reflections of the ultrasonic wave within the pipe to intersect the fluid profile in such a way as to get an average value of velocity [8].

1.2. Capacitive Ultrasonic Transducers

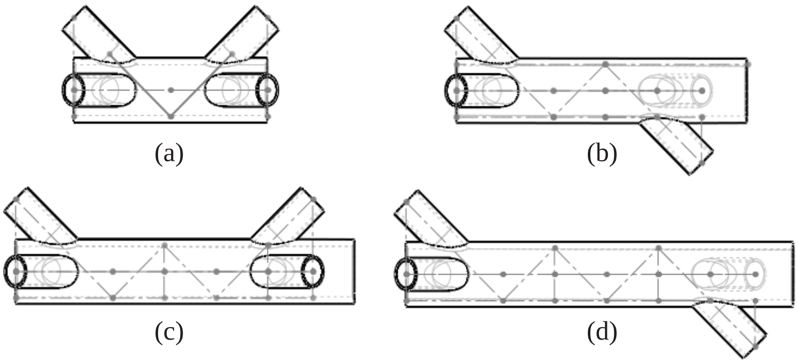
Ultrasonic transducers are designed both to generate and detect ultrasonic waves. Ultrasonic flow meters used for measuring flow rates in liquids typically use piezoelectric ultrasonic transducers, such transducers however show poor impedance matching in gaseous media, i.e. poor transfer of wave energy from the transducer into a gas [2]. The capacitive ultrasonic transducer is more commonly used in applications involving the propagation of ultrasonic waves in air due to its improved impedance matching performance. Such transducers are however not very rugged, and may also require a high bias voltage [9].

The capacitive ultrasonic transducer is, in principle, simply a parallel plate capacitor where an electrical force or an external acoustic force changes the distance between a thin flexible membrane electrode and a rigid back plate electrode, i.e. it initiates a mechanical vibration [9]. A DC bias is applied between the back plate and the membrane which builds up a charge between them and has the effect of stretching and distorting the membrane. A wave is then generated by an applied AC voltage which is proportional to the applied signal. Conversely the sensing function of the transducer converts an ultrasonic vibration picked up by the membrane into an AC voltage which is in turn proportional to the incident vibration. The frequency response of the transducer is largely determined by the mechanical properties of the membrane and the surface profile of the back plate electrode [2, 10]

2. EXPERIMENT

The metering section used in this work consisted of a smooth Perspex tube with an internal diameter D of 63.5mm, with transducer ports fitted at an angle of 45° to the tube axis. The various flow meter configurations shown in Figure 1 were obtained by the use of interchangeable coupling sections which varied in length and were used to join the upstream and downstream transducer port sections of the metering tube. Straight unobstructed pipe was connected for 20D upstream and 10D downstream respectively to produce a fully developed flow in the metering section. The test rig was connected to a compressed air supply which was throttled through a variable area rotameter to give a maximum flow of 100 litres/min at ATP.

The receiving transducers were connected to separate Cooknell CA6/C amplifiers, the outputs of which were then connected via a 15 kHz high pass noise filter to a Tektronix TDS 200 series oscilloscope. A bias voltage of l00V DC was applied to each of the receivers via the integral Cooknell SU2/C power supply. The transmitters were connected to an AVTECH AVRH-1-C pulse generator with a repetition rate of 100Hz, a pulse width of 1μs and a pulse amplitude of 100V. They were also connected to a DC power supply providing a 100V bias voltage. The positions of the transducers were adjusted so that the waveforms of the upstream and downstream paths coincided exactly, and the ultrasonic path length L determined from the transit time at zero flow and the speed of sound in air at the recorded air temperature. The



(a) (b)

(c) (d)

Figure 1: The four meter configurations: (a) “V”, (b) “Z”, (c) “W”, and (d) “VZ” with 1, 2, 3 and 4 ultrasonic reflections respectively

propagation times t_1 and t_2 for the upstream and downstream paths respectively were then recorded from the oscilloscope under varying flow conditions up to 100 litres/min.

3. RESULTS

Table 1 shows the calculated velocities for each volumetric flow rate and the corresponding velocity measured using the ultrasonic flow meter, with the appropriate Reynolds number *Re*, which show that the flow is laminar up to about 70 litres/min (i.e. $Re < 2000$) and transitional thereafter (i.e. $2000 < Re < 4000$). Values for the Reynolds number however do not account for the effect of the transducer ports on the flow. Figure 2 shows a comparison of the four flow meter configurations, where it can be seen that the longer path lengths are tending to overestimate the flow in the metering section while the shorter sections are tending to underestimate it. Issues with resolution may have affected linearity but would not account for any differences in the slope as the linearity is good in all cases. The effects of vortices formed in

Flow rate (l/min)	Calculated Velocity (m/s)	Measured Velocity (m/s)	Reynolds number
10	0.0741	0.0644	280
20	0.1483	0.1402	560
30	0.2224	0.2083	840
40	0.2966	0.2613	1120
50	0.3707	0.3598	1400
60	0.4448	0.4279	1680
70	0.5190	0.4961	1960
80	0.5931	0.5756	2241
90	0.6673	0.6285	2521
100	0.7414	0.7041	2801

Table 1: Velocities and Reynolds numbers for the V-configuration transit-time flow meter

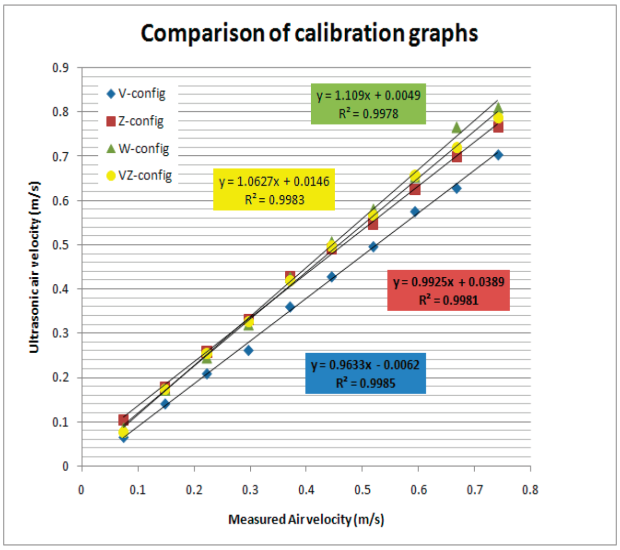


Figure 2: Calibration graphs for the four flow meter configurations.

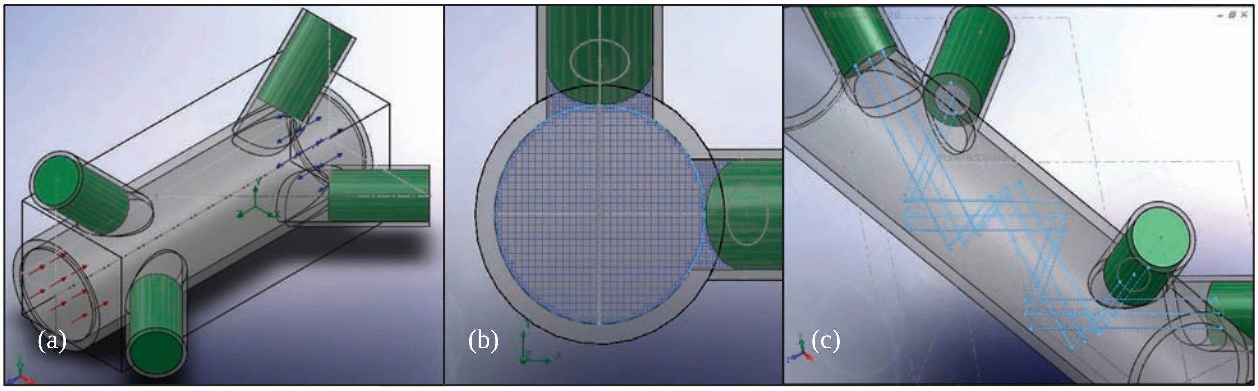


Figure 3: CFD model showing (a) metering section with boundary conditions, (b) typical mesh density within the metering section, and (c) chord measurements along the ultrasonic paths.

the transducer ports may also have had an effect, and the shorter path lengths may be more prone to the effects of this phenomenon.

3.1. CFD Modelling

CFD models were completed using SolidWorks COSMOSFloWorks™ for each flow meter configuration for representative flow rates of 40, 70 and 100 litres/min. The inlet boundary conditions were specified in terms of volumetric flow rate as a fully developed flow profile, so that it was not necessary to model the 20*D* of straight pipe upstream of the metering section. The outlet of the metering section was specified as a static pressure boundary, and similarly it was not necessary to model the 10*D* downstream of the metering section. This saved computational time and allowed a denser computational mesh to be employed in the model.

Figure 3(a) shows the geometric model of a typical metering section with the inlet and outlet boundary conditions (red and blue arrows, respectively). Figure 3(b) shows a typical mesh with a higher density in the transducer port cavities. Figure 3(c) shows three chords along each ultrasonic path. The models showed little effect due the transducer ports as the diametric velocity profiles for chords at different positions relative to the transducer ports showed little or no deviation from one another. However it should be remembered that the fluid flow here was

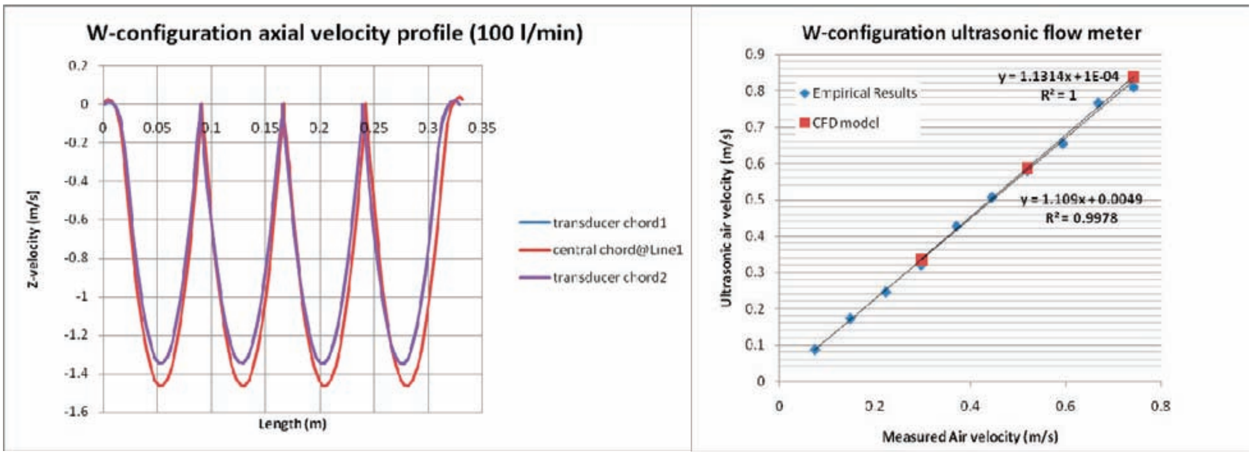


Figure 4: (a) Typical velocity profiles along the ultrasonic path chords, and (b) a comparison of the experimental and CFD flow results, for the “W”-configuration meter.

laminar and results for turbulent flows may yield different results.

A typical velocity profile obtained along the path chords shown in Figure 3(c) is shown in Figure 4(a), where the flow along the central chord is higher than the two identical side chords, as expected, and that the port cavities had a minimal effect as can be seen from the left and right extremities of each plot. These profiles were then used to find the average axial velocity along the ultrasonic paths by integrating the curves and dividing by the path length *L*. This was performed for a number of different volumetric flow rates for each configuration, and compared to the theoretical bulk average velocity in order to determine a correction factor from the CFD model. These graphs were then compared to the actual calibration graph as obtained from the ultrasonic test rig, as shown in Figure 4(b) for the "W"-configuration flow meter. It can be seen from Figure 4 that the CFD models show good correlation with the results from the ultrasonic test rig. The deviation between the experimental results and the CFD model varied between 9.6% for the "Z"-configuration and 1.9% for the "W"-configuration. There may be an optimum configuration and path length for a given pipe diameter, with shorter path lengths overly influenced by the transducer port geometry and longer path lengths experiencing the effects of beam attenuation. It should be noted that the chords are only representative of the ultrasonic paths, as the beam will be offset by the flow, the ultrasonic beam will spread out along the path, and that attenuation phenomena will affect the longer path lengths. The CFD models are thus models of the fluid flow only, and do not model the behaviour of the ultrasonic beam.

3.2. A Study of Installation Effects

In order to undertake a more detailed analysis of the effects of the transducer ports it was decided to subject the metering section to more complex flow profiles using an out of plane double bend at various distances upstream of the metering section. This was designed to cause a characteristic swirl flow profile as described in depth in [8]. The test rig was modified accordingly and the new configuration was also modelled using COSMOSFloWorks™ as shown in Figure 5 for the bends (a) 2*D* and (b) 10*D* upstream of the meter section. Velocity profiles were extracted for a number of applied volumetric flow rates and representative profiles at 100 litres/min are shown in Figure 6 for bends (a) 2*D* and (b) 10*D* upstream. It can be seen in Figure 6(a) that the flow profile is quite complex due to the close proximity of the out of plane double bend, although the flow profiles may also be affected in the central region of each profile

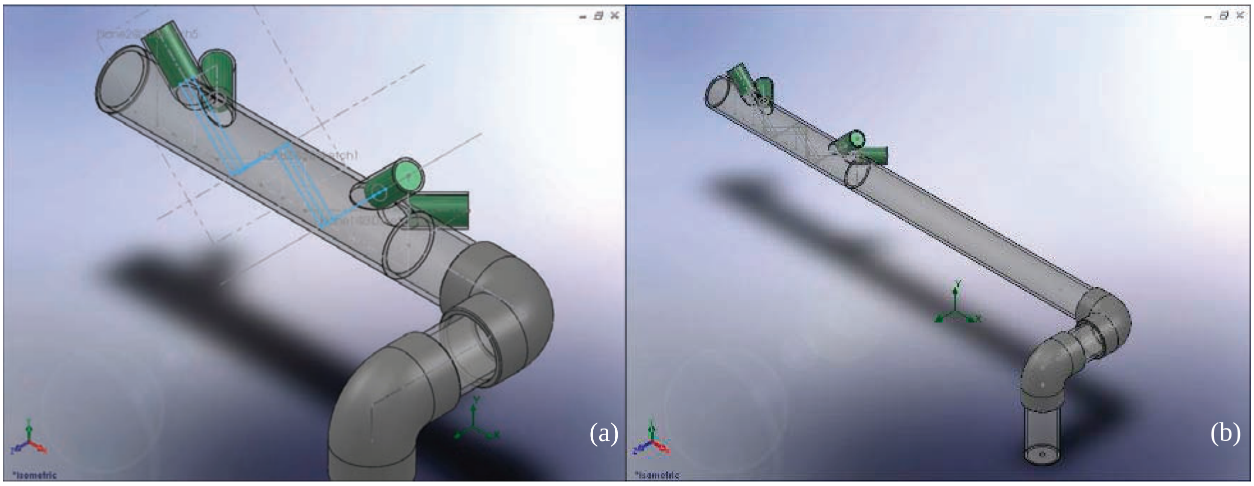


Figure 5: CFD geometry of out of plane double bend for typical distances of (a) 2*D* and (b) 10*D* upstream of the metering section

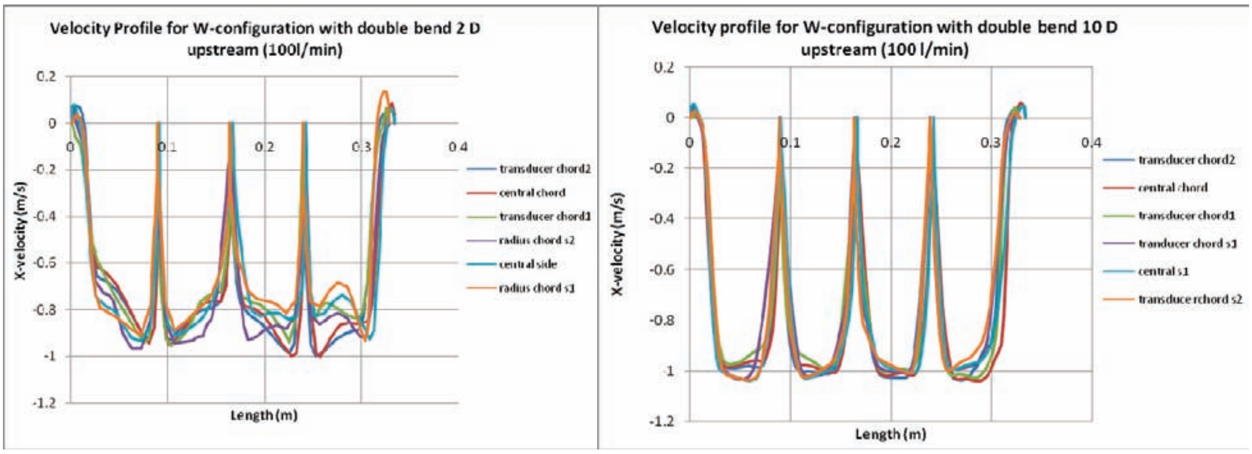


Figure 6: CFD velocity profiles along different transducer chords for an out of plane double bend (a) 2*D* and (b) 10*D* upstream of the metering section.

due to the coarseness of the computational mesh. Figure 6(b) for 10*D* upstream shows less complex velocity profiles, although these are still more distorted by the presence of the bends than the unobstructed profiles shown in Figure 4(a).

It can be seen from the comparison of CFD and empirical results shown in Figure 7 that in this case the CFD models tends to underestimate the flow possibly due to the low mesh resolution in central areas. Considering the empirical results in isolation, the installation effects are clearly visible in that the correction factor has decreased significantly in comparison to the value obtained for the same metering section configuration with 20*D* of straight pipe upstream. The unobstructed correction factor in Figure 4(b) was 1.109, compared to a value of 1.029 in Figure 7(a) for 2*D* and 0.991 for in Figure 7(b) for 10*D*. There is good overall correlation between the CFD models and the experimental measurements. The CFD modelling did not attempt to simulate the behaviour of an ultrasonic beam in a flowing media, and was just used to determine the average axial component of velocity along the approximated path in order to arrive at a correction factor. The mesh resolution used in the model was also restricted by the

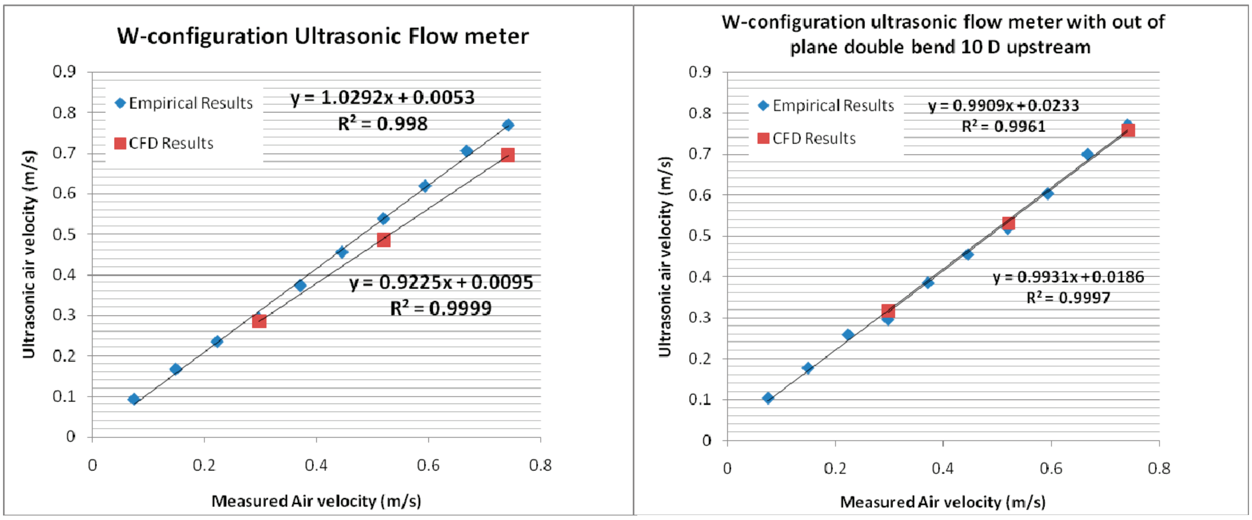


Figure 7: Comparison of CFD and experimentally measured (ultrasonic) flow velocities for an out of plane double bend (a) 2*D* and (b) 10*D* upstream of the metering section.

complexity of the models. In the out of plane double bend geometries it was necessary to reduce the mesh density so that models would solve. Even so, the mesh still had approximately 200,000 nodes, ran through 270 iterations and took about twelve hours to solve each individual model.

4. CONCLUSIONS

A detailed study has been undertaken of prototype ultrasonic transit-time flow meters using capacitive ultrasonic transducers. Experiments using a test rig for a range of airflows determined benchmark correction factors of 0.9633, 0.9925, 1.109 and 1.0627 for the “V”, “Z”, “W” and “VZ” configurations respectively. The flow meter configurations were modelled using SolidWorks COSMOSFloWorks™. A range of volumetric flow rates was simulated and theoretical correction factors from the mean velocity along the ultrasonic paths from the CFD models were determined to be 1.016, 1.088, 1.131, and 1.136 for the “V”, “Z”, “W” and “VZ” configurations respectively, with 20*D* of unobstructed straight pipe upstream. The CFD correction factors showed good correlation with experiment, with only a 2% difference between the empirical and CFD correction factors for the “W”-configuration.

In order to consider more complex flows the test rig was modified by installing an out of plane double bend at various distances upstream of the metering section. Experimental correction factors of 1.0292 and 0.9909 were determined for the “W”-configuration with the out of plane double bends 2*D* and 10*D* upstream, respectively. CFD models gave correction factors of 0.9225 and 0.9931 for the same geometries. Compared to the benchmark experimental correction factor of 1.109 it could be seen that installation effects 10*D* upstream of the metering section still had a major effect on the correction factor. There was no obvious relationship between the correction factor and the proximity of the bends to the metering section, which highlights the complexity of the flow in the test rig, which will be the focus of future work.

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