Liquid flow measurement using silicone polymer wedge clamp-on ultrasonic transducers

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Abstract:

Accurate liquid flow measurement is vital to many industries, and the benefits and limitations of ultrasonic transit-time clamp-on measurements are well understood. The ultrasonic transducers used in high quality clamp-on systems tend to be high cost items, containing an ultrasonic wedge of machined polyether ether ketone plastic (PEEK). PEEK is used because of its consistency and favourable ultrasonic properties of relatively low attenuation and consistent ultrasonic wave velocity over a wide range of frequencies. The viability of a new, high performance and low cost design of clamp-on ultrasonic transducers is described, made from a silicone based polymer moulded inside a shell and directly bonded to the active piezoelectric element. In addition to the reduced material and production cost, the new transducers have good thermal stability, consistency, conform well to the surface of the pipe. Tests were performed on a flow rig and on calibration blocks for thermal stability tests, showing that the sensors are of comparable performance to quality devices constructed using PEEK wedges.

Key words: liquid flow measurement; clamp-on ultrasonic transducers; transit-time difference; silicone rubber; thermal stability

1. Introduction

Liquid flow measurement is essential in many industrial applications [1]. The use of ultrasonic transit-time clamp-on devices is widespread and is one of a range of flow measurement tools used in industry. There are several alternative flow meter technologies and each one has a unique principle of operation, overall cost-of-ownership, and specific application benefits [2]. Compared with other flow meters [2-5], clamp-on ultrasonic transducers (CUTs) exhibit significant operational and economic advantages such as inexpensive to install and maintain and have a broader flow rate measurement range [6]. Moreover, CUTs can be easily mounted on existing pipe and provide a non-intrusive and completely non-invasive measurement of flow [2].

CUTs have been developed for about 70 years [7] and different mechanisms have been adopted to measure liquid flow rate, such as Doppler, cross-correlation and transit-time measurement [7, 8]. While Doppler CUTs remain an excellent solution for dirty liquids [9], transit-time CUTs have been showing faster growth in recent years due to their high accuracy [10, 11]. Today, there are over 20 world leading manufactures have and are developing the transit-time CUTs [12], including GE, Siemens, KROHNE etc. The research findings reported here relate specifically to the design of a new type of transit-time CUT.

There are many parameters that will affect the accuracy of clamp-on ultrasonic transit-time measurements, including alignment tolerance, electrical cabling, whether true reciprocal operation is performed and contributions to inaccuracy from electrical impedance differences or differences between the electromechanical properties of the transducers themselves. This paper considers only the design of a new type of clamp-on ultrasonic sensor, and as important as they are, does not consider the wide range of other factors that affect the overall accuracy performance of a system.

The research objective of this paper is to design and construct a new clamp-on transducer using a castable polymer wedge material, replacing the conventional wedge materials such as machined polyether ether ketone plastic (PEEK), while the performance of the new transducer is comparable to or better than conventional designs of ultrasonic clamp-on transducer. An additional advantage of using a castable polymer to form the ultrasonic wedge in a CUT, is that the dramatically lower material and construction cost (approximately fifty times lower cost than a PEEK wedge) reduces the overall cost of the technology, and lowers the barrier to technology adoption. Moreover, the polymer rubber has good thermal stability over the working temperature between -60 °C and 200 °C, which can guarantee the accuracy and consistency of the transit-time measurement.

Within the CUTs, there are 2 core components needed to generate and detect and propagate the ultrasonic waves: the piezoelectric ceramic and the wedge-shaped material that introduces sound waves into the pipe at an angle to the surface of the pipe. Conventional CUTs use PEEK wedges, which have consistency and favourable ultrasonic properties of relatively low attenuation and consistent ultrasonic wave velocity over a wide range of frequencies. But they are usually operated significantly below the glass transition temperature of 143 °C of PEEK [13], which limits their applications on high temperature flow measurements in petrochemical refineries and electricity generating power plants [14]. Buffer waveguides can be used to separate the ultrasonic transducers from the hot pipes [14], and some commercial flow meters have improved the working temperature up to about 400 °C by using extension wedges [15] or wave injectors [16]. However, these parts add complexity and cost to the CUTs. The piezoelectric material used in CUTs is typically an efficient form of lead zirconate titanate ceramic (PZT), such as PZT-5H, which is limited to recommended operation temperatures of <100 °C, but piezoelectric materials with lower efficiencies but higher operation temperatures, such as BiT, can be used of up to 450 °C or higher. In this study, a new low cost and easy to manufacture transducer wedge material is proposed, which can operate at a wider temperature range (-40 °C to 300 °C). In Section 2, the theory and mathematics are expressed in detail and Section 3 describes the new CUT design. The experimental setup is introduced in Section 4 and experimental results and analysis are presented In Section 5.

2. Theory and mathematics of the transit-time CUTs

2.1 Working principle of transit-time CUTs

The basic configuration of transit-time CUTs is the Z-configuration where the transducers are placed on opposite sides of the pipe so that the ultrasonic wave travels along in a direct transmission, as shown in Figure 1. The top transducer sends an ultrasonic wave travelling through the wedge material that is then refracted as it enters the pipe wall. The angle of the wedge is usually chosen so that the compression wave travelling through the wedge is mode converted to a shear wave that enters the pipe wall, and this is done beyond the critical angle where there is no compression wave in the pipe wall. This shear wave then refracts and mode converts to a compression wave in the liquid (which cannot support a shear wave). The compression wave will travel through the flowing liquid in the direction of the flow (downstream direction) and will then be received by the bottom transducer in figure 1, after passing through the pipe wall and wedge material, undergoing the reciprocal refraction and mode conversion stages that were described for the generation of the ultrasonic wave in the liquid. Simultaneously, some guided waves will also be generated and travel along and around the pipe wall, which can be detected by the other transducer. This process is then reciprocated, with the two transducers switching roles as generator and detector, with the ultrasonic compression wave in the liquid travelling against the direction of the flow (upstream direction).

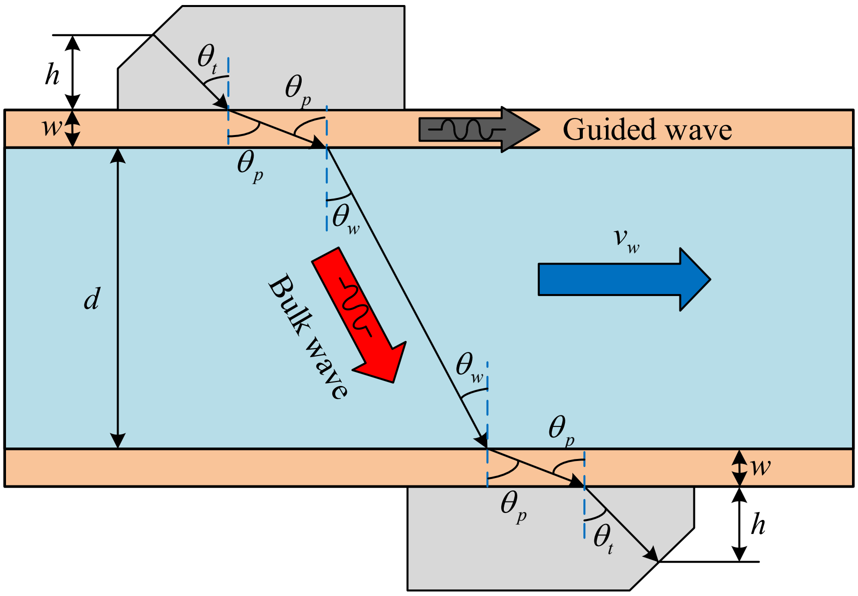


Figure 1. Schematic diagram showing the transmission path of ultrasonic waves between two transducers with Z-configuration.

Normally, the propagation of guided waves is hardly affected by the flow velocity, and the sensors will be arranged so that the guided waves that travel along the pipe wall and waves that have travelled through the liquid are clearly separated in time. The transit-time CUTs will measure the transit-time of bulk waves that propagate through the liquid, pipe walls and wedges, but the difference between the two arrival times when propagating upstream and downstream are only dependent on the average flow velocity of the liquid along the ultrasonic propagation path if temperature is constant. The downstream and upstream travelling time t_{down} and t_{up} can be calculated as [2]

$$t_{down} = \frac{2h}{\cos\theta_t c_t} + \frac{2w}{\cos\theta_p c_p} + \frac{d}{\cos\theta_w (c_w + v_w \sin\theta_w)} \tag{1}$$

$$t_{up} = \frac{2h}{\cos\theta_t c_t} + \frac{2w}{\cos\theta_p c_p} + \frac{d}{\cos\theta_w (c_w - v_w \sin\theta_w)} \tag{2}$$

where h is the distance between the center piezoelectric ceramic and the pipe outer surface; w is the pipe wall thickness; d is the inner diameter of pipe; θ_t is angle of wedge; θ_p and θ_w

are the refraction angles in pipe and liquid, respectively; c_t, c_p and c_w are the ultrasonic velocity in wedge, pipe and liquid, respectively; v_w is the liquid flow velocity.

Definite measurement of t_{down} and t_{up} is usually calculated by some type of cross-correlation [17], which may also include some modulation or encoding of the transmit signal to improve the reliability of the algorithm. The time difference Δt between t_{down} and t_{up} is calculated in this paper [3],

$$\Delta t = t_{up} - t_{down} = \frac{d}{\cos\theta_w(c_w - v_w \sin\theta_w)} - \frac{d}{\cos\theta_w(c_w + v_w \sin\theta_w)} = \frac{2dv_w \tan\theta_w}{(c_w^2 - v_w^2 \sin^2\theta_w)} \tag{3}$$

As the liquid velocity is much smaller than the ultrasonic velocity in liquid [2], so $c_w^2 \gg v_w^2 \sin^2\theta_w$. Equation (3) can be simplified as

$$\Delta t \approx \frac{2dv_w \tan\theta_w}{c_w^2} \tag{4}$$

Therefore, the liquid flow velocity can be calculated as [3]

$$v_w = \frac{c_w^2 \Delta t}{2d \tan\theta_w} \tag{5}$$

This can be modified to incorporate multiple paths in the liquid within the bore of the pipe

$$v_w = \frac{c_w^2 \Delta t}{2Nd \tan\theta_w} \tag{6}$$

where N is the number of ultrasonic paths in the liquid.

In equation (6), the ultrasonic velocity in liquid c_w varies with temperature [2]. The refraction angle θ_w depends on both the wedge angle and the ultrasonic velocities in different mediums based on the Snell's law. The wedge angle can be fixed before the measurement and the refraction angle also varies with temperature. The denominator part Nd depends on the transducer configuration and the pipe geometry. This part can be calibrated in advance, as the parameters associated with them remain constant during a measurement. Thus, the flow velocity is directly proportional to the time difference Δt.

2.2 Signal processing for transit-time difference calculation

The time difference between the upstream and downstream signals can be quite small (< ns) at low flow rates [3]. To measure Δt accurately, a cross-correlation method is used to calculate the time delay between the downstream and upstream ultrasonic signals [18]. The general definition of the cross-correlation function is

$$(f * g)(\Delta t) = \int_{-\infty}^{\infty} \overline{f(t)} g(t + \Delta t) dt \tag{7}$$

where $f(t)$ and $g(t)$ represent the downstream and upstream ultrasonic signals, respectively; Δt is the time difference between them; $\overline{f(t)}$ denotes the complex conjugate of $f(t)$.

2.3 Reynolds number and flow profile correction

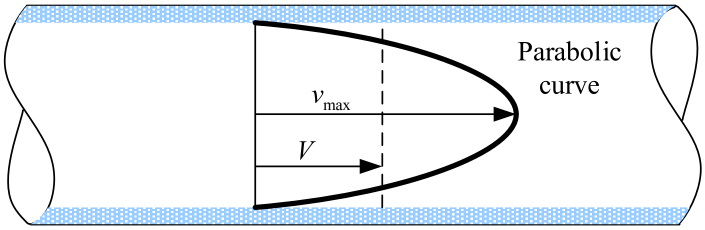
The Reynolds number is a dimensionless parameter used to describe the flow regime in different flow situations [2], which can be used for predicting if the flow is laminar or turbulent. The Reynolds number for a pipe flow can be calculated as follows [19]:

$$Re = \frac{\rho d v_w}{\mu} \tag{8}$$

where Re is the Reynolds number; ρ is the liquid density (kg/m^3); μ is the dynamic viscosity (Pa·s).

At low Reynolds numbers ($Re < 2000$), the pipe flow tends to be dominated by laminar flow, while at high Reynolds numbers ($Re > 2000$), the flow transitions into turbulent flow [19].

Based on the Reynolds number, the type of flow regime and the shape of the flow profile can be predicted. The flow velocity profile in the pipe changes from parabolic at laminar flows to a more uniform profile at turbulent flows [20], as shown in Figure 2.



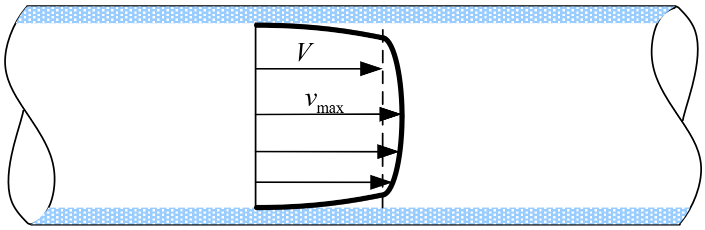


Figure 2. Flow profile in a pipe from [20]. Dashed lines indicate average flow velocity.

It can be seen that the ultrasonic wave travels through the flow with varying local velocities which the transducers measure as a line-average velocity [8]. This average however fails to account for the actual velocity distribution across the pipe cross section which in reality is two dimensional [21]. A flow profile correction factor (FPCF) is needed in order to accurately determine the flow velocity and therefore the mass flow rate. The FPCF k_h is defined as

$$k_h = \frac{v_w}{v_{measured}} \tag{9}$$

The FPCF is a parameter depending on the Reynolds number [22]. Typically k_h has a value of 0.76 for laminar flow and 0.94 for turbulent flow [23]. Then the mass flow rate can be calculated from the flow velocity

$$v_{mass}(\text{kg/min}) = 60 \cdot \rho v_w \frac{\pi d^2}{4} \tag{10}$$

3. New clamp-on ultrasonic transducer (CUT) design

Figure 3 shows the geometry of the CUT, which includes a piezoelectric ceramic and a wedge-shaped material that the ultrasonic wave propagates through. The piezoelectric ceramic used here is modified PZT-5H plate with a resonant frequency of 1 MHz from PI ceramic [24], which has high permittivity, large coupling factor and high piezoelectric charge coefficient. The ceramic is bonded to the inclined surface of the polymer wedge during the casting of the wedge material.

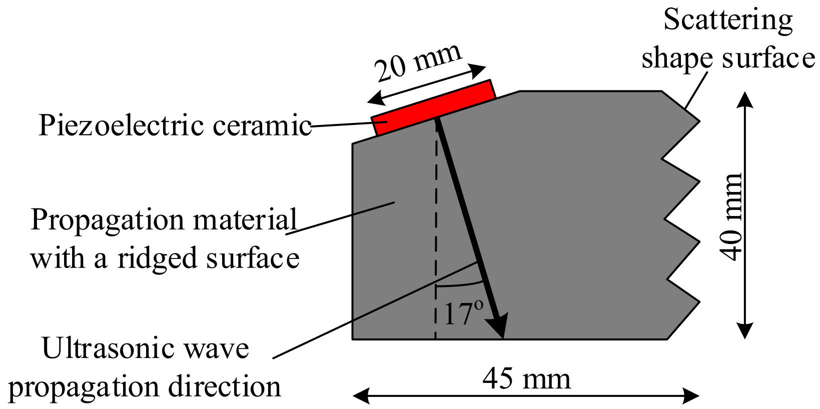


Figure 3. Schematic diagram of the new CUT illustrating components and direction of wave propagation (not to scale). In this case the piezoelectric element is a 2 mm thick (1 MHz), 10 mm wide, 20 mm long PZT-5H piezoelectric that is bonded to the rubber wedge.

When the ultrasonic wave arrives at the boundary between the wedge and the pipe wall, the waves can be either refracted into the pipe or reflected back into the wedge. The reflected waves can cause interference within the wedge and so a scattering shape surface on the side opposite to the piezoelectric ceramic is created to dissipate any reflected waves. The level of attenuation achieved is at least greater than 30 dB, but whilst desirable making the signals easier to visually interpret, strictly speaking it is not always necessary to completely attenuate a reverberating signal. As long as the signals from each transducer are very similar (even if they have reverberations), the signal processing used such as correlation can usually deal with any reverberations. It is however still good practice to design a transducer in which multiple echoes within the wedge are minimized. This is achieved by inserting an ABS plastic component into the mould with the inverse profile desired in the rubber wedge. The exact profile of this scattering edge is not important, provided that it scatters waves that would otherwise enter the pipe after multiple reflections within the wedge. The exact geometry of the wedge is not important, except for the angle of the piezoelectric required to satisfy Snell's law and that the position of the scattering edge is close enough to the piezoelectric to prevent a wave reverberating within the wedge from entering the pipe.

The conventional CUTs use a wedge made from PEEK, which is relatively expensive in its own right, and can have significant machining and assembly costs when building a CUT. PEEK has a glass transition temperature T_g of approximately 143 °C [25] and beyond this temperature, PEEK begins to lose its rigid 'glass' structure and its acoustic properties will change, making the transducers less efficient and accurate above this temperature [6]. In this study, we use a castable silicone polymer ("Ultracouple" from Sonemat Ltd [26]) as the wedge material, that is approximately one fiftieth of the cost of PEEK, and because it is castable assembly is straight forward and manufacturing of the new CUT is low cost. The silicone polymer has a T_g value of -120 °C, however it can display excellent acoustic and mechanical properties between -60 °C and 200 °C and can operate up to 370 °C [27]. The material properties of the silicone polymer are shown in Table 1 [28]. Another advantage of the silicone polymer wedge is the lack of a significant shear modulus, which helps to reduce the shear wave propagation and wave mode conversion in the wedge. The scattering shape surface shown on the right of figure 3 are obtained by inserting 3D printed components or other formed parts, into the casing prior to casting the silicone polymer.

Table 1. Material properties and transmission coefficients [28].

Material	Compression wave velocity (m/s)	Density (kg/m^3)	Acoustic impedance (M Rayls)	T%
Epoxy	2658	1146	3.05	-
Silicone grease	980	967	0.95	-
Silicone polymer	920	1180	1.08	81.85
PEEK	2470	1310	3.24	67.81

Normally a layer of an adhesive or grease is used to bond or couple the piezoelectric ceramic to the wedge and also a thin layer of acoustic couplant (e.g. silicone grease) is required between the wedge and the pipe wall in practice. Assuming the thickness of the propagation medium is (2n+1)λ/4 (quarter wavelength or multiple), the transmission coefficient T of the ultrasound through a three-layered structure (epoxy, wedge material, silicone grease) may be written as follows:

$$T = \frac{4Z_1Z_2}{Z^2\left(1+\frac{Z_1Z_2}{Z^2}\right)^2} \tag{11}$$

where Z_1, Z_2 and Z are the acoustic impedances for the epoxy, silicone grease and the wedge material, respectively. The properties of a typical epoxy, silicone grease and PEEK and the calculated T values are shown in Table 1. The silicone polymer produces and enhancement of 1.2 over PEEK, which would be squared for transmit-receive operation.

4. Experimental setup

A schematic diagram of the flow rig system used in the experiments is shown in Figure 4.

This flow test rig was developed by the Cambridge University Engineering Department and its uncertainty of the measurement from commercial flowmeters is better than 0.1% [12]. The water flows from the bottom of the main sump tank to the water pump. Water flow is controlled by a pump speed controller. A flow conditioner is used close to the start of a straight section where the CUTs are tested further downstream, where the pipe run has a length of stainless steel pipe (ASTM A312) and ABS pipe to provide different pipe materials to test the CUTs. An electromagnetic (EM) flowmeter is positioned towards the end of this straight section of pipe, and the locations where the CUTs were tested are within the dashed red box shown in figure 4. Table 2 shows the dimensions and acoustic parameters of the stainless steel and ABS pipes.

Table 2. Dimensions and acoustic parameters of the stainless steel and ABS plastic pipes used for ultrasonic measurement [29].

Material	Outer diameter (mm)	Wall thickness (mm)	Density (kg/m^3)	Longitudinal velocity (m/s)	Shear velocity (m/s)
Stainless steel	60.3	3.91	7890	5790	3100
ABS	25	1.9	1050	2250	1150

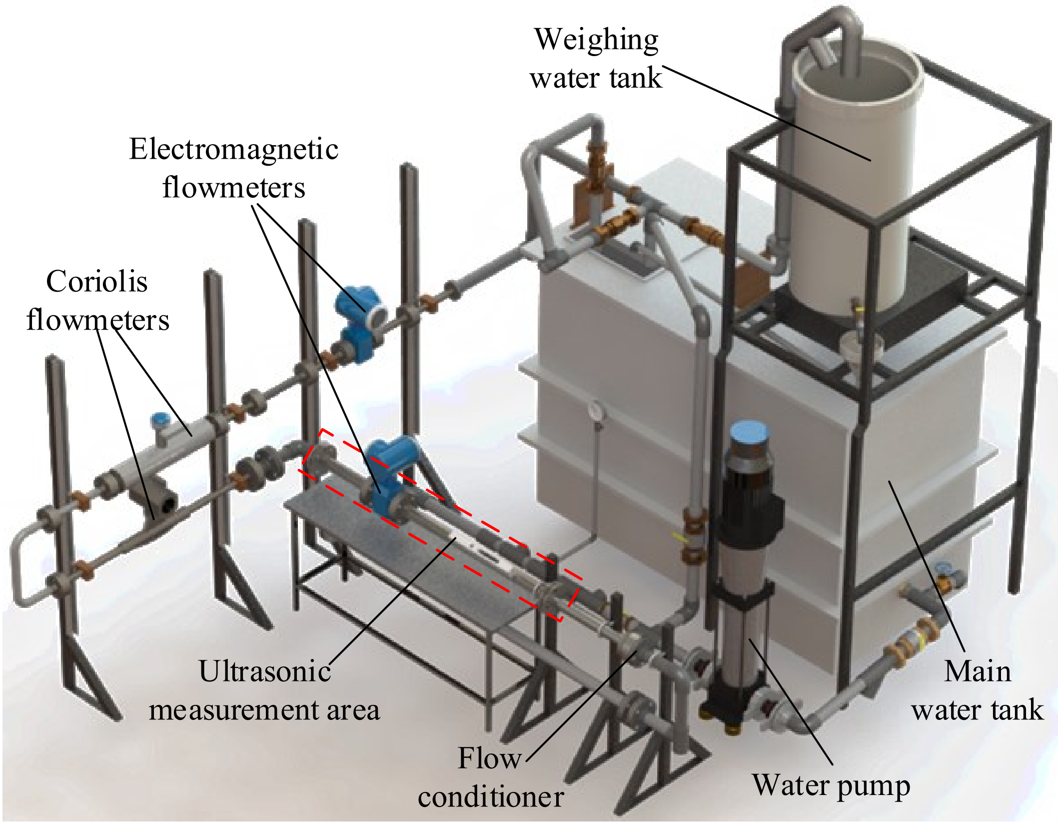
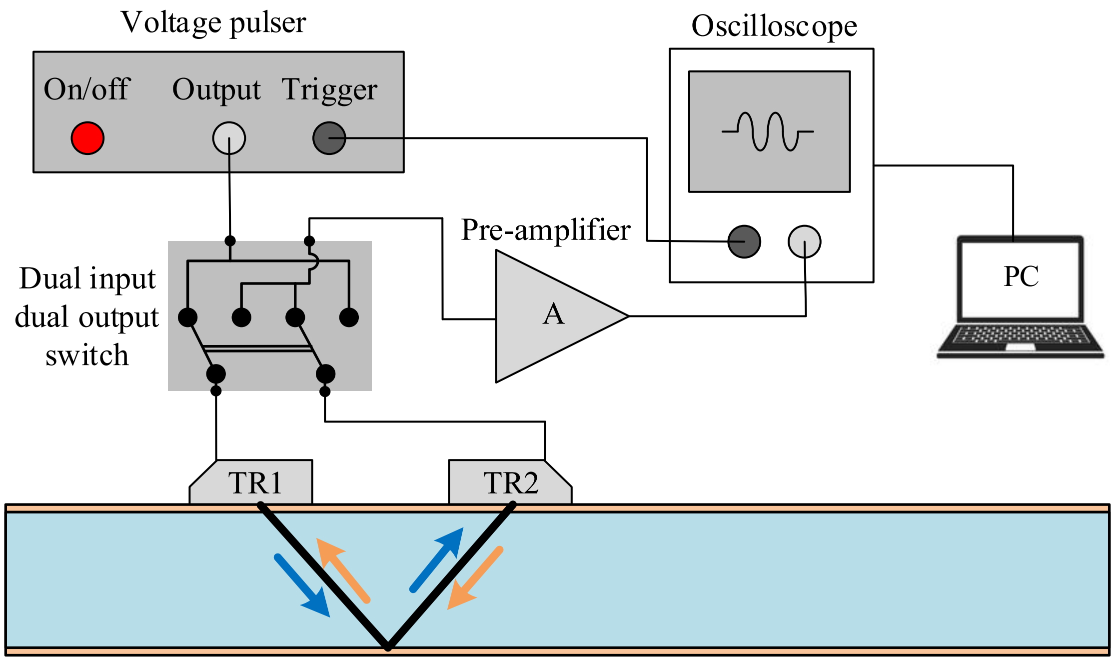


Figure 4. Schematic diagram of the flow rig system.

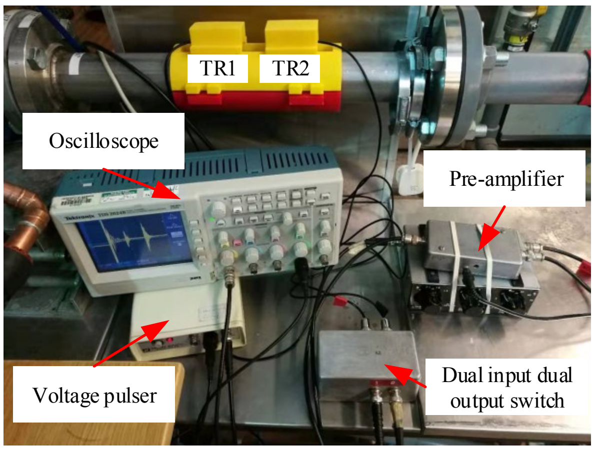
In addition to another EM flowmeter further downstream, the system has a further two Coriolis meters and a weigh tank that is periodically used to verify the calibration of the flowmeters in the system. The entire system is controlled from a computer, that also displays and records all the readings from the four commercial flowmeters and the weight scale, which are used to independently measure the mass flow rate. The averaged value of these commercial flowmeters is used to determine the accuracy and reliability of the various measurements using the new CUTs, as shown later in Section 5.

There are multiple possible configurations for transit-time ultrasonic flowmeters such as 'Z-path', 'V-path' and 'W-path etc. The 'V-path' configuration is used most commonly because it tends to cancel crossflow as well as crosstalk [30]. Moreover, it is the most convenient to set up on the same side of a pipe, usually with the CUTs being held within the same rail, and it also provides a longer path and measured transit-time difference through the liquid compared to ‘Z-path’ configuration [31]. Multiple reflection paths such as the W-path, may be used on small pipes to increase the transit-time difference measurement, but the waves travelling through the liquid attenuate with distance and the number of guided wave modes arriving at the detector can also increase with distance. Guided ultrasonic waves travelling along and around the pipe wall can arrive at the same times as the interfering with the desired waves that have been reflected up the pipe bore, through the flowing liquid. In this study, the ‘V-path’ and ‘W-path’ configurations were used for the stainless steel pipe (84.0 mm separation distance) and ABS pipe (31.9 mm separation distance). A thin layer of silicone grease (RS 494-124) with operating temperature between -50 °C to 200 °C is applied between the transducers and the pipe wall to ensure good acoustic coupling of ultrasonic waves between the materials, but with careful cleaning of both surfaces, this is not always strictly required. A pair of clamps were 3D printed to configure the alignment and distance between the two transducers, and they also help press the transducers on the pipe surface to maintain good contact and acoustic coupling.

Figure 5 shows the schematic diagram and photograph when the two CUTs were set up on the stainless steel pipe wall. The voltage pulser (Spike 100 PR from Walker Sonix) generated a 100 V half sine wave pulse (0.1 μs width) to the generation transducer and the other transducer served as a receiver. A switch was used to swap the transmitter and receiver to measure the downstream and upstream signal, respectively. The received ultrasonic signal was amplified by a homemade pre-amplifier circuit with 0-50 dB adjustable gain, and recorded by the oscilloscope. Then the data was transferred to a computer for further data processing. The lengths of cables and electronics were as similar as possible to minimize zero flow offset. Also zero flow offset calibration, which is due to the unaligned piezoelectric ceramics, was conducted before the tests to get the best accuracy.



(a) Schematic diagram



(b) Photograph

Figure 5. (a) Schematic diagram and (b) photograph of the experimental setup for the CUTs. Note that in the top schematic diagram, the optimum separation of the transducers needs to be calculated in each case and is different for the two transducers, with separations of 84.0 mm and 47.5 mm for silicone polymer wedge and PEEK wedge, respectively.

5. Experimental results and analysis

The CUTs were tested on both the stainless steel and ABS pipes across a range of flow rates.

Figure 6 shows the received ultrasonic “A-scan” signal on the stainless steel pipe at zero flow using the new CUTs and some similarly sized, high quality, commercial PEEK wedged transducers for comparison. A number of alternative PEEK wedge sensors were tested, exhibiting similar performance to each other. Remembering in these experiments that the drive pulse supplied to the transducers is a wideband wave pulse, the resulting A-scans will be indicative of the bandwidth of the transducers. In both A-scans of figure 6, there is a clear distinction between the guided wave travelling along the pipe wall and bulk wave that as travelled through the liquid in the V-path configuration. The voltage amplitude of the received ultrasonic signal of the new CUTs is almost identical to that of the PEEK wedged transducers, but the signal to noise ratio of the silicone polymer wedged transducers is significantly better, and more narrowband. The type of low frequency noise of figure 6 (b) is often observed when constructing other types of ultrasonic transducer where the piezoelectric element is attached to a rigid substrate. It appears that the low shear elastic modulus in the rubber material suppresses these other modes that most likely arise due to width or length modes of vibration of the piezoelectric element. This is an interesting phenomena and further work is required to determine the exact cause of these low frequency signals, that is beyond the scope of this current paper.

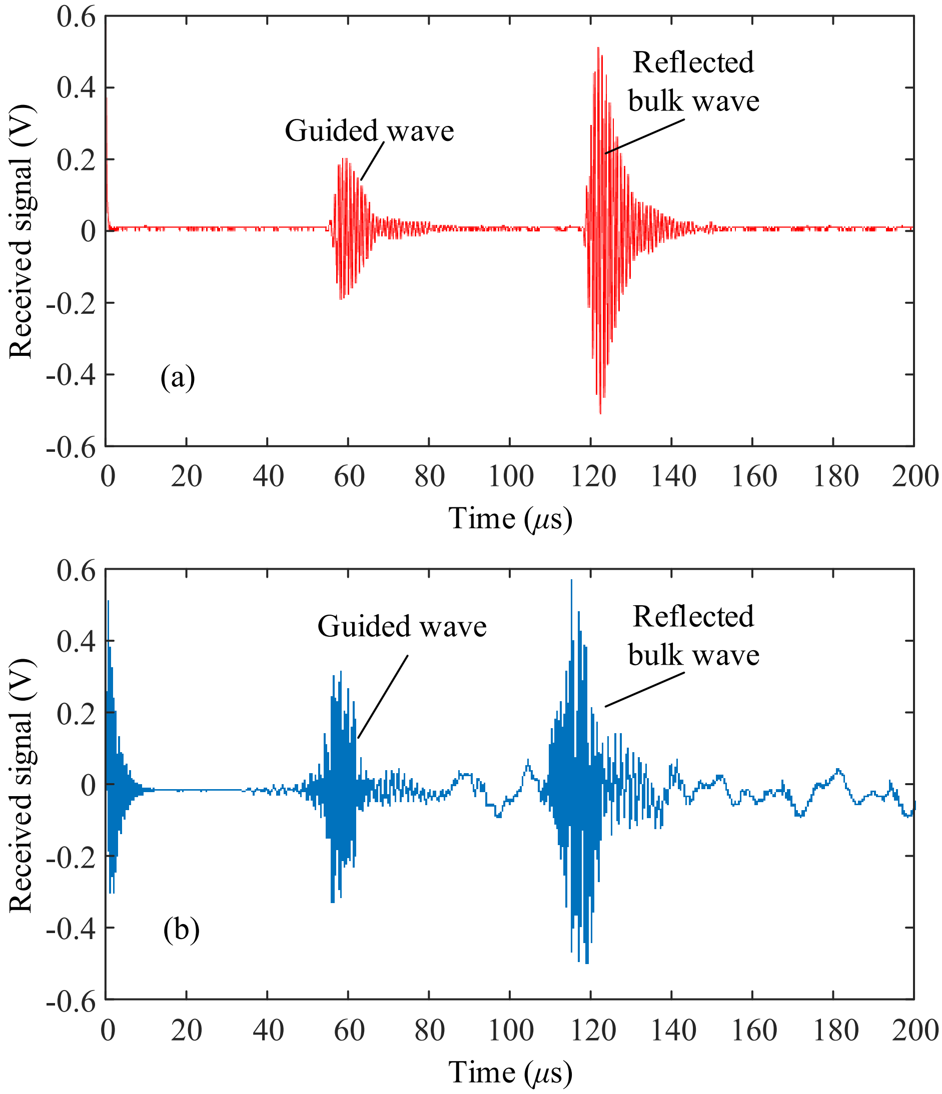


Figure 6. Received ultrasonic signal using (a) the new designed CUTs and (b) PEEK wedged transducers on the stainless steel pipe at zero flow, respectively. Note the generally cleaner appearance of the ultrasonic signal with the rubber wedge and the lower frequency background acoustic noise signal in the PEEK wedge. The front end electrical noise appears slightly longer in the result for the PEEK wedge material, because the rubber material has a stronger damping effect on the piezoelectric through thickness resonance mode. In real use, the front end noise before 20 microseconds is not an issue in any case.

Then the new CUTs were used to test the flow rate. As flow rate increases, the guided wave arrival time remains constant for all conditions. However, the signal from the wave that has travelled along the V-path moves backward or forward in time when measuring at upstream or downstream conditions, respectively, as shown in Figure 7. The time difference of this signal was measured to calculate the flow velocity. Note that even though there is evidence of some distortion of the waveform due to the large signal level with the preamplifier used, the cross-correlation of the signals still works well due to the very reproducible behavior of the rubber wedge transducers. Whilst using a different transducer or lower gain amplifier would reduce this level of distortion, it was decided to present this result to demonstrate that even where an amplifier may produce some level of signal distortion, the high reproducibility of the transducers mean that this is not an issue in real use.

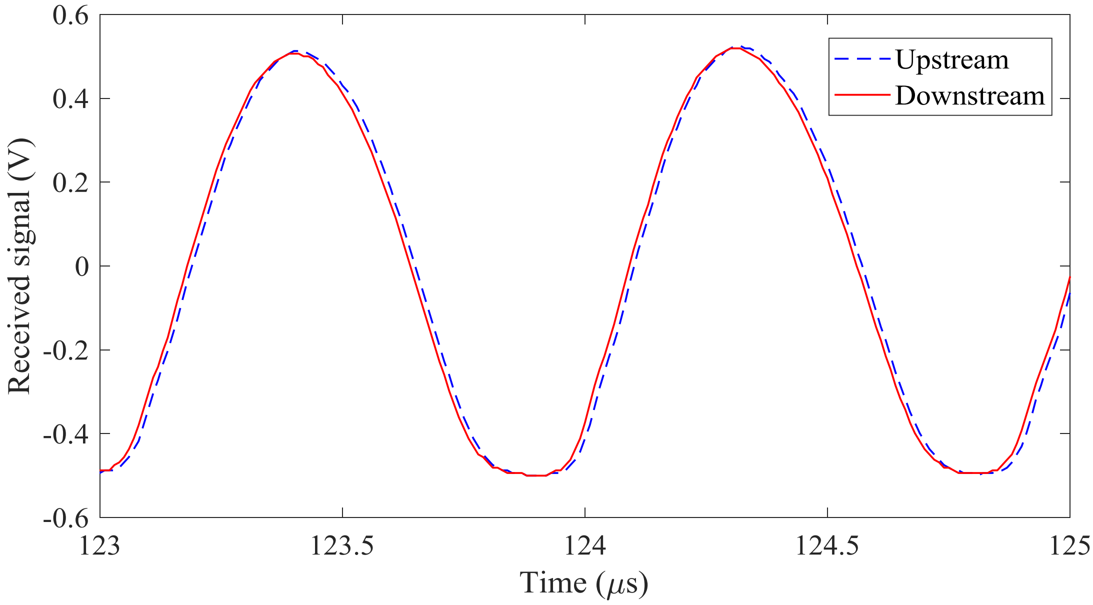


Figure 7. Reflected bulk wave signal on the stainless steel pipe when the flow velocity is not zero. Note that even though the waveforms show some evidence of distortion, particularly on the troughs, the consistency of the CUTs and the signal processing technique used ensures a high accuracy measurement of transit-time difference [18].

There are many different signal processing techniques that can be used to improve the reliability and calculation accuracy of the time difference measurement, and these are often dependent on the hardware used. In this case, the A-scan signals were processed as follows, before the cross-correlation calculation is performed.

(1) Smoothing data with moving averages. The signal suffers from digitization error, so a 100-point weighted moving average was used to smooth the waveform. A Gaussian function provides the weightings in the smoothing function.

(2) DC error correction. The small DC voltage offset from the amplifier was removed so the signal always oscillates about the zero voltage point.

(3) Interpolation between data points. The time resolution of the received signals is limited by the oscilloscope sampling frequency (1 GS/s). Lower flow rates require sub-nanosecond time difference resolution based on the Nyquist theorem. A linear interpolation of the points in the A-scan was used increasing the number of points in the waveform by a factor of 100, to increase the time resolution to 10 ps.

A cross-correlation function was then applied to the pre-processed signal to determine the time difference between the upstream and downstream signals. Figure 8 shows the relationship between the calculated time difference on the stainless steel pipe and the averaged mass flow rate taken by the electromagnetic and Coriolis flowmeters.

The mass flow rate measured by CUTs can then be calculated using Equations (6), (8) to (10). The velocity of ultrasound in water is about 1482 m/s at room temperature [32].

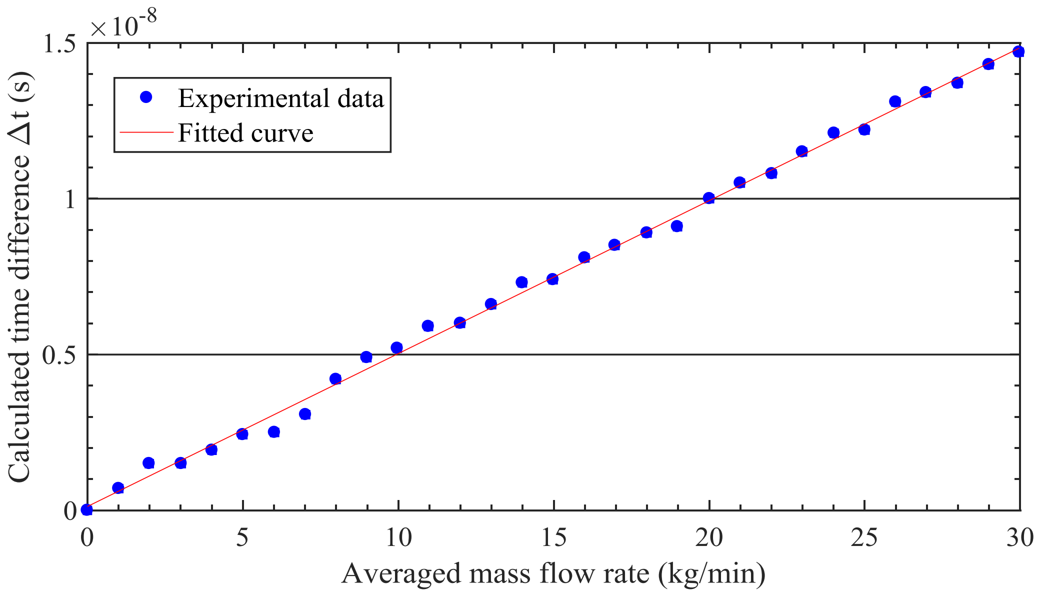


Figure 8. Relationship between the time difference and the mass flow rate.

Figure 9 shows the mass flow rate measured using the new CUTs on two different pipes. The black dotted lines are the upper and lower boundaries of the 5% error range. It can be seen that the mass flow rate measured by the CUTs shows good linear agreement with other commercial flowmeters. The two fitted curves have a similar gradient approximately equal to 1 with a difference of only 0.2% between them. The data points have a small deviation from the trend lines and most the measurements are within the 5% error range. The largest proportion of precision error is found at low flow rates (< 15 kg/min). In this preliminary experiment, a constant FPCF in equation (9) was used to calculate the mass flow rate. But this correction factor varies with Reynolds number [8] and it should be adjusted with varying flow rates to improve the measurement accuracy.

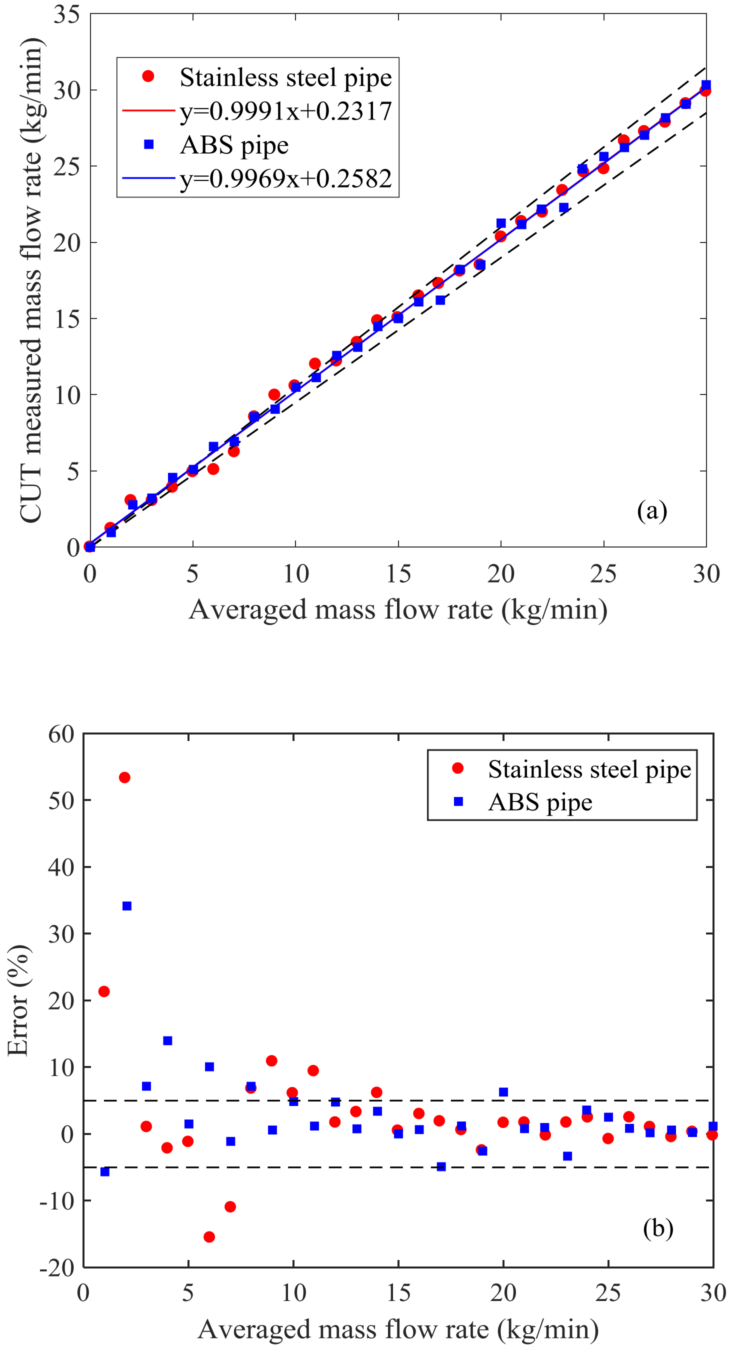


Figure 9. Performance of the new silicone polymer wedge CUTs on two different pipes. (a) The measured mass flow rate and (b) relative percentage error plots.

As expected, using the simple processing techniques described here, the results show a good linear trend and the small deviation from a gradient of 1, simply tells us that there is a calibration error with the correction factors that we used in this experiment. This can be easily corrected, by careful calibration with the flow rig and using the obtained empirical correction factors in the final flow rate calculation. As expected, low flow rates have a higher relative percentage error (maximum about 54% at 2 kg/min) as time difference measurements become very small, on a scale where the oscilloscope time jitter trigger becomes significant. In this preliminary demonstration of the sensors, the zero error could be introduced in the experimental procedure or due to the inhomogeneity and nonlinearity of pipe materials [33].

These flow measurement results are tested at room temperature and it is important that the new CUTs can work consistently over a wide temperature range. Therefore, the thermal stability of the CUTs was tested between -20 °C to +40 °C by attaching them to two opposite sides of an aluminium block (150 mm×100 mm×50 mm) in a Z-path type configuration. The time domain A-scan signal was captured and the transit-time of the shear wave transmitted directly across the block was calculated. Figure 10 shows the relationship between the transit-time and temperature, which shows the transit-time increases linearly with the increasing temperature. This is due to the small decreases of ultrasound velocity of the aluminium and silicone polymer wedge material when the temperature increases [34]. The results indicate that the new designed CUTs can work consistently with good thermal stability.

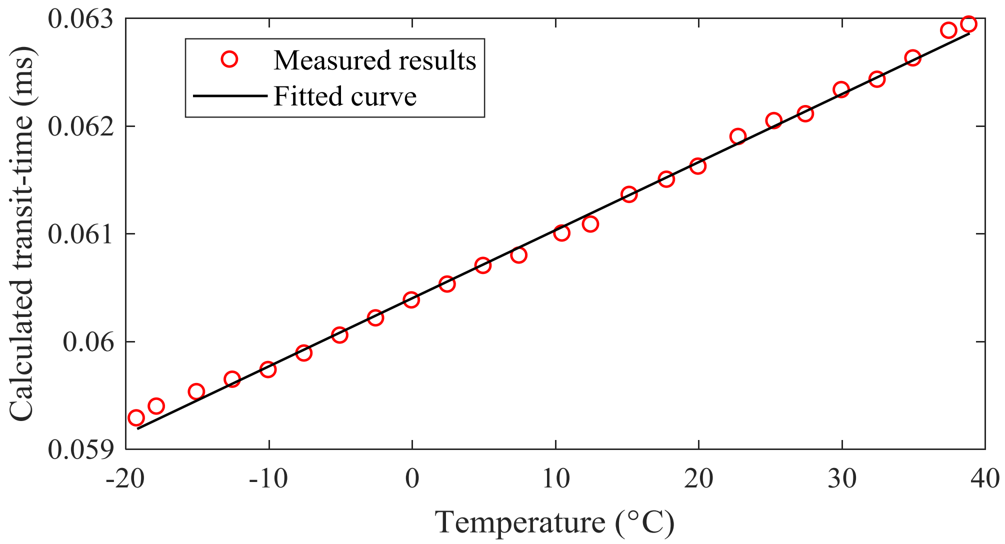


Figure 10. Relationship between the transit-time and temperature when the two new CUTs were fixed on an aluminum block.

6. Conclusions

The performance of the new silicone polymer wedge clamp-on ultrasonic transducers (CUTs) for liquid flow measurement has been validated and is consistent with the performance that can be obtained using PEEK or other rigid plastic wedges. The key conclusion is that the new CUTs have a significantly lower cost compared with the conventional PEEK transducers, due to the simple 3D printed shell and silicone polymer wedge material. In addition, the new transducers have good thermal stability, an improved coupling to the pipe wall and good transmission of ultrasound.

The new silicone polymer wedges can actually be dry coupled to clean pipes, but for optimum acoustic coupling a very small amount of grease or gel couplant should be used. The contact surface of the material is also slightly compliant, adapting to the shape of the pipe surface without loss of performance or accuracy. The effective inability of the silicone polymer wedge to support shear waves improves the consistency and quality of the ultrasonic pulse shapes generated and detected by the transducers, making signal processing of the transit time difference easier.

There are some factors that need consideration when using a silicone polymer wedge, the first being that after mixing and prior to casting the silicone, it requires degassing for a few minutes to remove any large bubbles. Once degassed though, a large amount of wedges can be cast from the same mixture.

The silicone is also slightly more attenuative than PEEK, and in representative tests, attaching two transducers either side of samples of rubber and PEEK with thickness of 14.3 mm and 15.0 mm respectively, the measured amplitude of the ultrasonic compression wave signals transmitted through as slab of material was approximately 0.1 dB/mm lower than measured in the PEEK at 1 MHz. This measurement is not true attenuation, as it neglects effects of reflection and transmission coefficients at the interface between piezoelectric transducer and rubber, but it is representative of realistic performance. This small increase of effective attenuation in the rubber is not a limiting factor on the operation for CUTs using the rubber wedge material.

Another consideration when fabricating a CUT, is that where the transducer is designed to be working within a critical angle, such that the compression wave incident on the pipe wall is mode converted to a shear wave, that the angle for this is steeper than is required for PEEK, primarily as the ultrasonic compression wave velocity is higher in PEEK. Because though the polymer rubber is cast into a highly reproducible mould, manufacturing tolerances are high and the steep angle does not appear to cause any issues.

There will always be a use and a place for PEEK as a wedge material in CUTs, but there are clearly many technical, fabrication and commercial advantages to using silicone polymer wedges in transit-time ultrasonic flowmeter transducers.

There are several areas which should be investigated further to explore potential commercial applications and environments. These include measurements on fluids of varying temperatures or pipes with a different geometry and varying materials.

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