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Contrapropagating Ultrasonic Flowmeter Using Clad Buffer Rods for High Temperature Measurements

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This work proposes clad buffer rods driven by shear transducers as the main building block of contrapropagating ultrasonic flowmeters for high temperature application. It is demonstrated that the superior signal-to-noise ratio exhibited by clad buffer rods (compared with the reported nonclad counterparts) improves precision in transit time measurements, leading to more accurate flow speed determination. In addition, it is shown that clad buffer rods generate specific ultrasonic signals for temperature calibration of flowmeters, allowing temperature variation while still measuring accurately the flow speed. On the basis of these experimental results, a contrapropagating ultrasonic flowmeter was designed and installed in a heater machine for flow speed measurements of hot oil at temperatures near 130°C. For a temperature variation of 3°C, the difference between upstream and downstream ultrasonic transit times, which is proportional to the flow speed at a given temperature, was measured within 1 ns accuracy.

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Keywords: high temperature ultrasonic measurement, contrapropagating flowmeter, clad buffer rods, water flow speed, oil flow speed

1 Introduction

The determination of the liquid flow speed is important for process optimization and control [1]. Among all available techniques for liquid flow evaluation, ultrasound is advantageous owing to nonintrusiveness, applicability to a large class of materials, robustness, and low cost. In fact, ultrasonic inspection of liquid flow at room temperature is a well-established technique [2]. However, several industrial processes, such as polymer extrusion, polymer injection molding, and metal die casting, demand high temperature flowmeter systems for in-line monitoring and control of the melt flow speed. The difficulties encountered by ultrasonic measurement of flow speed and other processes at elevated temperatures are related to the Curie point of the ultrasonic transducer (UT) piezoelement, disbonding between the electrode and the epoxy backing material, and ultrasonic couplant [3]. These drawbacks may be overcome if a suitable buffer rod is interposed between the UT and the process liquid. The typical problem of using buffer rods is the appearance of spurious signals due to dispersion, multipaths, mode conversion, and beam spread (diffraction loss) [4]. Thus, new materials and buffer rod configurations have been developed recently in order to reduce spurious signals and allow flow speed measurements at high temperatures [3]. In these works, an ultrasonic contrapropagating flowmeter was designed employing a *hockey stick* buffer rod with superior waveguidance just for shear waves. This novel configuration could then successfully generate longitudinal waves for sensing the liquid flow. However, no attempts have been reported to cancel out the effect of temperature variation in flow measurement. Due to the rapid

temperature variation that the melt flow of industrial processes may undergo, there is an urgent need of developing sensors and techniques immune to temperature variation.

The concept of clad buffer rods (CBRs) for ultrasonic monitoring of materials and processes have been reported in several applications [5–16], and owing to certain advantages (superior wave guidance, robustness, machinability, and capability to stand high temperature and pressure) [17], their performance for flow speed measurements at high temperature is now investigated.

In this contribution, we intend to demonstrate that in the standard contrapropagating ultrasonic flowmeters, CBRs exhibit superior signal-to-noise ratio (SNR) compared with the reported non-clad rods in through-transmission mode. A high SNR is desirable for more accurate evaluation of flow speeds [18]. In addition, specific ultrasonic signals in CBRs can be used for temperature calibration of flowmeters. Such a feature, which is explored for the first time herein, affords temperature variation while still measuring accurately flow speeds.

2 Theoretical Background

2.1 Contrapropagating Ultrasonic Flowmeter. In contrapropagating ultrasonic flowmeters flow speed is obtained by measuring, over the same path, the time difference between two ultrasonic waves traveling downstream and upstream [19]. The acoustic waves can be transmitted simultaneously, but typically they are alternated in order to avoid interference between them [20,21]. In terms of flowmeter realization, ultrasonic sensors are placed either on opposite facing surfaces or on the same side. Here, we focus on the latter configuration for two basic reasons: It can be mounted on duct surfaces with limited access, and it also enlarges the acoustic travel time difference inside the flow, which enhances resolution in time-domain measurements. In this case, downstream (t_d) and upstream (t_u) travel times are found by vector operation [22],

$$t_d = \frac{L^2 + 4D^2}{c\sqrt{L^2 + 4D^2} + vL} \quad (1)$$

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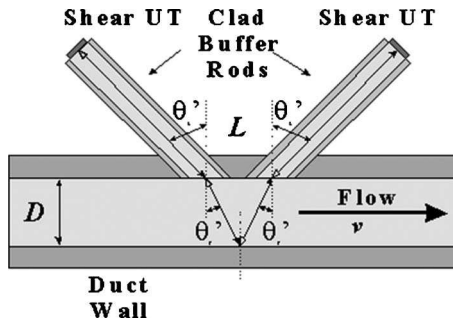


Fig. 1 Weld-in contrapropagating ultrasonic flowmeter. Shear wave UTs are used to transmit and receive ultrasonic pulses.

$$t_u = \frac{L^2 + 4D^2}{c\sqrt{L^2 + 4D^2} - vL} \quad (2)$$

where L is the axial interaction length between ultrasonic beams, D is the distance perpendicular to the axis between ultrasonic beams, c is the ultrasonic velocity in the fluid, and v is the average flow speed along the path, as shown in Fig. 1. Indeed, if the ultrasonic velocity c were known accurately enough or remained constant, the average flow speed v could be determined by transmission in one direction only (using either Eq. (1) or Eq. (2)), similar to what is normally done by the beam deflection method [20]. For most flowing liquids, however, c is usually 300–700 times larger than v . Therefore, if the fractional uncertainty in c is not exceedingly small, it is not possible to measure v to 1% or better unless transmission in both directions (i.e., contrapropagation) is used to cancel c out [20]. Such an important feature of the contrapropagation approach is better appreciated by assuming that c is invariant during measurements of t_d and t_u . Hence, c can be eliminated from Eqs. (1) and (2) to yield

$$v = \frac{L^2 + 4D^2}{2L} \left(\frac{1}{t_d} - \frac{1}{t_u} \right) \quad (3)$$

Equation (3) indicates that the average flow speed is a function of downstream and upstream acoustic travel times and duct geometry. Furthermore, it is no longer dependent upon ultrasonic velocity c , justifying why the contrapropagation method is by far the main flowmeter technique applied in industrial environments [19].

It is always desirable that during flow measurement the sensor does not disturb the interrogated flow at all. In the contrapropagation method, this can be achieved by means of different installations of buffer rods and UTs over the duct, being the weld-on, weld-in, and clamped-on configurations the most popular [20]. For industrial fluids subjected to severe conditions of temperature and pressure, those techniques are safe and effective. Whenever allowed, the weld-in configuration is the simplest one to analyze for acoustic wave propagation is limited to the buffer rod and fluid only. Weld-on and clamped-on versions are more complex because the duct is encompassed by the buffer rod and fluid, requiring knowledge about material properties and thickness of the duct wall for proper flowmeter design. Besides, the wall surface may also complicate the acoustic coupling to the fluid. These reasons suggest the weld-in type as the one to be analyzed and implemented in this work. Such an approach eliminates the coupling problem by setting the buffer rod probing end flush to the inner surface of a rectangular duct wall.

Although two distinct sources, namely, longitudinal and shear wave UTs, can be used in connection with chamfered buffer rods to generate the sensing signals of contrapropagating ultrasonic flowmeters, only longitudinal waves are transmitted through the liquid since fluids in general do not support shear motion. The reason shear waves, under certain conditions such as polarization and incidence angle, can generate longitudinal modes at the inter-

face of two different media is explained by the mode conversion property of the oblique incidence [23,24]. To introduce a few key concepts on contrapropagating ultrasonic flowmeters design, let us estimate the angle at which the ultrasonic waves propagating in a chamfered buffer rod enter the liquid. For steel CBRs, the longitudinal wave velocity in the core is about 6000 m/s at 25°C, and the shear wave velocity is about 3300 m/s [19]. At high temperature, e.g., 200°C, these values are reduced a few percent (less than 5%) [19]. For simplicity, the velocity variation will be neglected in this first calculation. In hot water at 200°C, the longitudinal wave velocity is further reduced to about 1000 m/s [18]. Assuming 40 deg incidence angle from steel to water at 200°C, the angle of refraction is calculated according to Snell's law [22,23]. If the longitudinal mode is transmitted, the angle of refraction in water is found to be about 6.1 deg. Instead, if the shear mode is chosen, the refracted angle becomes about 11.2 deg. Thus, for the same angle of incidence and propagation media, the shear mode incidence results in a larger angle of refraction than longitudinal. Consequently, the propagation path in water and the corresponding transit time difference Δt between upstream and downstream transmissions are also enlarged. To put it in a quantitative way, we subtract Eq. (2) from Eq. (1) and assume $c \gg v$ to obtain

$$\Delta t = t_u - t_d \approx 2(v/c^2)L = 4(v/c^2)D \tan \theta'_r \quad (4)$$

where θ'_r is the angle of refraction in water (to the normal of the surface), as shown in Fig. 1. In this example, therefore, the transit time difference measured by employing shear UTs is 1.8 times greater than that measured by longitudinal UTs. Clearly, shear UTs are preferable over longitudinal ones for the weld-in contrapropagating flowmeter proposed herein: The resolution in time difference to be measured is increased about 80% as well as the axial interaction length $L = 2D \tan \theta'_r$ between transmitter and receiver probes. Since UTs cannot be scaled down at will, the latter feature may be an extra advantage in some specific applications. Hence, the ultrasonic flowmeter to be implemented and tested in this work is illustrated in Fig. 1, with shear UTs playing the role of both transmitter and receiver.

3 Design of a Contrapropagating Ultrasonic Flowmeter With Clad Buffer Rods

Before attempting liquid flow measurements at high temperature, the performance of CBRs as part of a contrapropagating flowmeter should be assessed. For this purpose, water flow at constant room temperature (the simplest alternative) is selected for initial tests. It has been seen that if the temperature is kept constant or varies slightly over the period in which ultrasonic signals are acquired, the contrapropagating approach is convenient for measuring flow speeds because it is not necessary to know the ultrasonic velocity in the liquid medium. In this work, however, we will make use of Eq. (4) as the ultrasonic velocity in water is a well-known parameter [19,20]. Its advantage is that one needs to measure only the difference in transit times, rather than their absolute values. Thus, characterization of the CBRs is carried out in an immiscible water tank, which exhibits high thermal capacity.

As the first design criterion for the flowmeter configuration of Fig. 1, a proper angle for the CBRs must be decided. We chose 40 deg incidence, corresponding theoretically to approximately 94% of the maximum coupled energy between probes. Detailed analysis can be found in the literature [25,26].

3.1 Comparison Between Clad Steel Buffer Rods and Non-clad Buffer Rods for Contrapropagating Ultrasonic Flowmeter Design. Cross-correlation is a well-known technique for measuring downstream and upstream transit times in contrapropagating ultrasonic flowmeters [18]. Accurate transit time measurements require that spurious noises in the buffer rod do not interfere with the desired ultrasonic signals. It has been reported that steel CBRs are superior to nonclad counterparts for

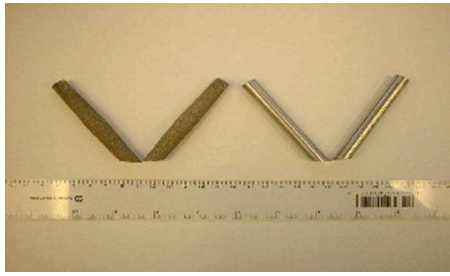


Fig. 2 Pairs of steel clad (left) and nonclad (right) buffer rods selected for performance comparison in through-transmission mode

wave guidance in pulse-echo mode [17], leading to high SNR (e.g., $\text{SNR} \geq 35$ dB). Here, our aim is to verify, in through-transmission mode, the SNR superiority of CBRs over nonclad rods for use in contrapropagating flowmeters.

Figure 2 shows steel buffer rods selected for this comparison. One pair (at the left) is clad by the thermal spray technique [17], while another pair is nonclad rods. The cladding material is stainless steel. They have approximately the same length, and each of their probing ends is cut at the same angle of 40 deg. Commercial 5 MHz shear UTs (6.35 mm element diameter) attached to the flat end of the buffer rods and operated in through-transmission mode were used for signal generation and detection. Each pair of steel CBRs and nonclad buffer rods were aligned with respect to a steel plate reflector immersed in water, lying 1 cm from the probing end surfaces, as illustrated in Fig. 3. Signals acquired for each configuration and frequency spectra of the $S^1-L_1-S^1$ echo (the one that travels in the transmitter rod, water, and receiver rod) are shown in Fig. 4. It is noted that the signal amplitude for the case of CBRs is 6 dB stronger than that obtained from nonclad rods. The superior SNR of CBRs compared with the nonclad rods is expected to improve precision in transit time measurements by the cross-correlation technique, leading to more accurate flow speed determination. In addition, detection of the S^1-S^1 echo is possible only with CBRs. The explanation and application of the S^1-S^1 echo are given later in this paper. Here, it can be said that the $S^1-L_1-S^1$ echo is used to sense flows in contrapropagating flowmeters.

4 Building and Testing the Ultrasonic Contrapropagating Flowmeter With Clad Buffer Rods in Water Flow at Room Temperature

Before evaluating the contrapropagating flowmeter with CBRs at high temperatures, we started by building a prototype to be

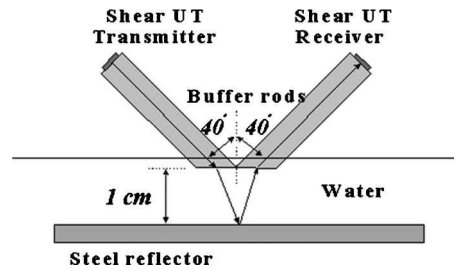


Fig. 3 Experimental configuration for evaluating buffer rod performance in through-transmission mode

tested in water at constant room temperature. This test is intended mainly to ascertain the accuracy of flow speed measurements. In order to minimize errors due to temperature variation and flow profiles, two considerations are taken into account here. First, flow speed measurements are carried out in a water tank with high thermal capacity. Since the temperature is constant, the average flow speed is proportional to the difference between downstream and upstream transit time measurements. Second, this proportionality holds if the ultrasonic beam interrogates the entire cross-sectional area of the duct; otherwise, integration techniques based on additional ultrasonic probes along the duct sectional periphery or numerical correction factors have to be used to average the flow speed measurements [27]. Therefore, we selected a stainless steel duct with square sectional area whose dimensions are roughly the diameter of the buffer rod core (5 mm). Thus, ultrasonic beams interact with a large section of the flow profile.

The duct in which the contrapropagating flowmeter was assembled is 151 mm long, with internal edge measurement being $D=10$ mm (see Figs. 1 and 3). In order to install the chamfered CBRs flush with the duct inner surface, a small rectangular hole was made in the duct top wall to accommodate the CBR probing ends. For the materials involved (i.e., steel and water at 25°C), Snell's Law determines the separation L between the centers of the probing ends to be $L=2D \tan \theta'_r=6.11$ mm [27]. 5 MHz shear UTs operating in through-transmission mode were clamped on the CBRs and sealed to prevent their electrical terminals from being attacked by water. Due to the 1.5 mm thick cladding, the precise separation L of 6.11 mm could not be met. Instead, the probing ends were situated 12 mm apart, which is still within the -3 dB amplitude range [27]. Finally, the ultrasonic probes were aligned with respect to the duct walls. The resulting flowmeter prototype was then fixed in the center of the water tank turntable, as shown in Fig. 5. One extremity of the duct was connected via a hose to

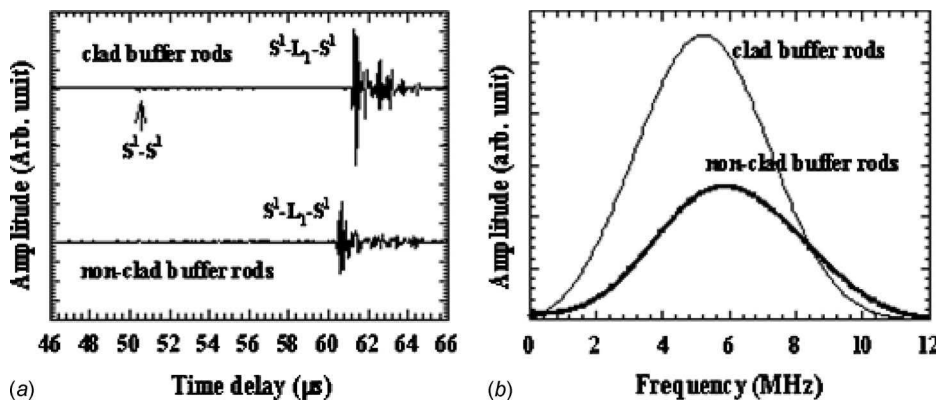


Fig. 4 Experimental results obtained for the configuration shown in Fig. 3. (a) Time domain signals. (b) Frequency spectra of the $S^1-L_1-S^1$ echoes shown in (a).

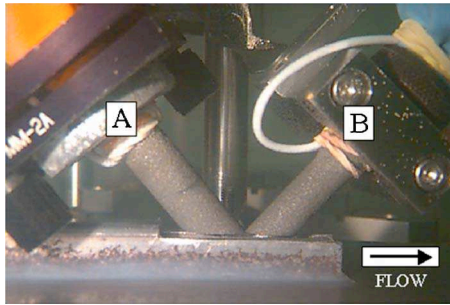


Fig. 5 A contrapropagating ultrasonic flowmeter prototype for water flow measurements at room temperature. For downstream transit time measurements, probe B is the receiver; for upstream transit time measurements, probe A is the receiver.

the water input terminal of the tank. The tank was also equipped with a regulator valve to control the flow rate. It was verified that the water flow input could be up to 2 m/s.

The use of the designed flowmeter requires calibration at the operating temperature (25°C) to account for unexpected differences between downstream and upstream transit times at zero flow speed. This difference may be attributed to the fact that the UTs used as transmitter and receiver (and vice versa) are not identical [28]. Signals recorded for downstream (probe B as receiver) and upstream (probe A as receiver) are shown in Fig. 6. These signals were acquired at 125 MHz sampling rate and averaged 50 times. Cross-correlation time delay measurements, performed with LABVIEW® software toolbox [26], revealed a difference between downstream and upstream times of 6.112 ± 0.7795 ns. This is the calibration factor used for measurement corrections.

Excluding the valve at closed position, four other apertures were selected to control the flow rate. The corresponding flow speeds were determined by measuring the volume rate (VR) provided in the output of the square duct through the well-known equation $VR=Q/A$, where Q is the flow (volume/time) and A is the cross-sectional area of the square duct. Measurement results were averaged ten times, and the maximum ratio of standard deviation to average flow speed was about 1%. Owing to this repeatability, these values were used as flow speed standards to be compared with ultrasonic measurements through Eq. (4). Using the same procedure adopted for the flowmeter calibration, upstream and downstream signals were acquired ten times, compensated by the calibration factor and finally substituted into Eq. (4). The results are shown in Fig. 7. It is observed that ultrasonic measurements were repeatable, and the error bars intersected with the theoretical curve. As expected from the theoretical calculation, experimental results exhibited linear relationship between the difference in transit time and the flow speed. An accuracy of the order of 1 ns has been achieved.

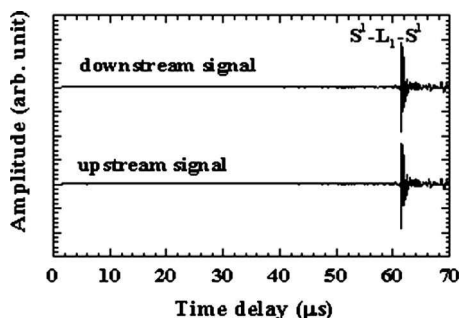


Fig. 6 Typical ultrasonic signals obtained with the flowmeter prototype in Fig. 5

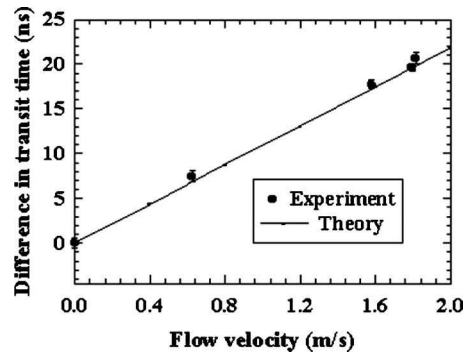


Fig. 7 Experimental and theoretical results for the contrapropagating ultrasonic flowmeter shown in Fig. 5

5 Building and Testing the Ultrasonic Contrapropagating Flowmeter With Clad Buffer Rods in Oil Flow at Elevated Temperature

A Thermocast™ heater machine provides flow of Shell Thermoia® oil Cat temperatures near 130°C. This machine is used to demonstrate the high temperature flow speed measurement by the flowmeter. Because of the different operating temperature and liquid media considered now, buffer rod angles and separation L between probes have to be re-evaluated. An incident angle of 40 deg is still an effective design value [27]. Due to high impedance mismatch between steel and Thermoia-C oil at 130°C, there is a decrease of the ultrasonic energy transmitted into the oil and detected by the flowmeter [27]. The angle of refraction in hot oil is further reduced, yielding $L=4.99$ mm. Thus, the cladding close to the probing end was partially removed, resulting in a minimum separation $L=8$ mm. A flowmeter was then implemented. The CBRs were welded into the duct wall, flush with the duct inner surface. Figure 8 illustrates the CBRs installation, fans to cool down the CBR UT extremities, and three type-K thermocouples to sense the temperature of the flowmeter in the vicinities of the CBRs. The temperature data are sent over a GPIB interface to the Pentium® PC, and the LABVIEW® program acquires temperature and ultrasonic signals simultaneously.

Proper functionality of the flowmeter system at high temperature, such as generation and detection of ultrasonic signals, proper cooling of the UTs, and absence of hot oil linkage, have been verified. Typical ultrasonic signals acquired for downstream and upstream operations are shown in Fig. 9. It was demonstrated earlier that the superior SNR of the CBRs over the nonclad rods leads to detection of two echoes, namely, S^1-S^1 and $S^1-L_1-S^1$. Figure 10, which is intended to illustrate the ultrasonic beam paths

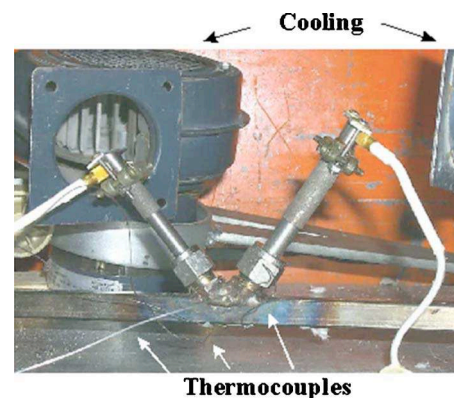


Fig. 8 Implementation of the contrapropagating ultrasonic flowmeter designed for high temperature operation

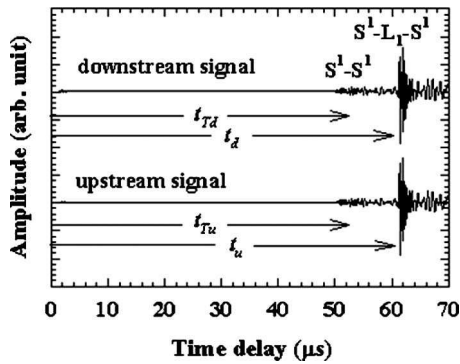


Fig. 9 Typical ultrasonic signals obtained with the contra-propagating ultrasonic flowmeter shown in Fig. 8

in the designed flowmeter, explains the origin of such echoes. The S^1-S^1 echo is originated by shear waves propagating along paths 1,2,3 and 3,2,1 for downstream and upstream operations, respectively. Its transit time is t_{Td} or t_{Tu} , shown in Fig. 9, where d and u subscripts stand for downstream and upstream, respectively. The $S^1-L_1-S^1$ echo propagates as shear waves in the transmitter CBR and is converted into longitudinal waves in the solid/liquid interface. After sensing the liquid, longitudinal waves are converted back into shear waves in the liquid/solid interface and are finally detected by the receiving shear UT. For downstream and upstream measurements, $S^1-L_1-S^1$ propagates along paths 1,4,5,3 and 3,5,4,1, respectively. Accordingly, the transit times associated with these paths are t_d or t_u . Thus, downstream signals are characterized by a pair of transit times (t_{Td}, t_d) , while upstream signals are characterized by (t_{Tu}, t_u) .

It has been observed that downstream and upstream transit times t_{Td} and t_{Tu} of the S^1-S^1 echo are linearly related with the average temperature measured by thermocouples simultaneously with the acquisition of the ultrasonic signals. For instance, at zero flow rate in the output of the Thermocast™ machine, this linear relationship is shown in Fig. 11. In this figure, the temperature is the average value of three thermocouples. Therefore, measurement of transit times t_{Td} and t_{Tu} offers a means to calibrate the flowmeter with respect to the temperature of the flow. In other words, t_{Td} and t_{Tu} may be used as temperature reference to ascertain that downstream t_d and upstream t_u transit times have been taken at the same temperature. This is the essence of the temperature effect compensation here proposed in order to reduce measurement errors in the contra-propagating flowmeter. It is possible because the SNR of CBRs is high enough to reveal the existence of the S^1-S^1 echo in contrast to the reported nonclad rods.

In order to demonstrate the technique of temperature effect compensation thus devised, downstream and upstream signals were acquired nonsimultaneously for three different scenarios:

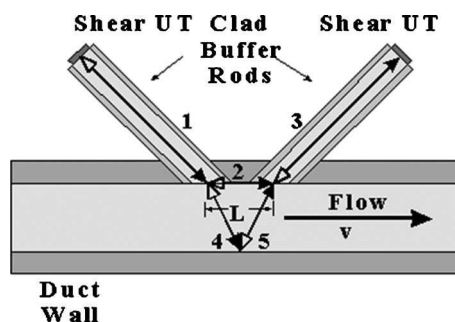


Fig. 10 Ultrasonic beam paths in the contra-propagating ultrasonic flowmeter

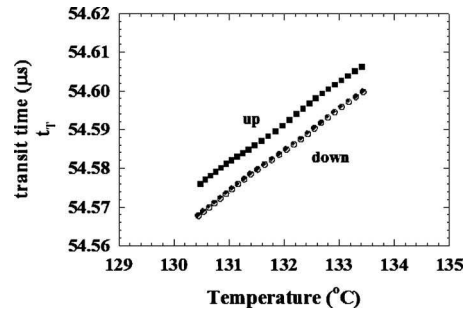


Fig. 11 Linear relation between the average temperature in the liquid flow and the ultrasonic transit times (upstream and downstream) of the S^1-S^1 echo for the flowmeter shown in Fig. 8. The oil flow speed is zero.

maximum flow rate provided by the Thermocast™ machine, 60% of the maximum flow (intermediate flow) rate, and zero flow rate. In all cases, acquisitions started at temperatures around 134°C, prolonging until about 130°C. Signals were acquired at 50 MHz sampling rate and averaged 50 times. Acquisitions were estimated to take one averaged signal per second. For each flow rate, the downstream and upstream pairs (T, t_T) (thermocouple temperature and S^1-S^1 transit time, respectively) and (t_T, t) (S^1-S^1 and $S^1-L_1-S^1$ transit times, respectively) were stored in the PC. The common temperature T for downstream and upstream operations was then found, resulting in the pairs (t_{Td}, t_d) and (t_{Tu}, t_u) . At this point, Eq. (4) holds to determine flow speed from measurements of downstream and upstream times at the same temperature. Equivalent to the pairs (t_{Td}, t_d) and (t_{Tu}, t_u) are the new pairs $(t_{Td}, t_d - t_{Td})$ and $(t_{Tu}, t_u - t_{Tu})$. The latter takes into account the propagation of $S^1-L_1-S^1$ in liquid paths 4,5 and 5,4, respectively, rather than in solid paths 1,3 and 3,1, as seen in Fig. 10. However, it was noted that at zero flow rate upstream and downstream curves do not match, as mentioned in Sec. 4 and illustrated in Fig. 11. This means that a calibration factor must be applied to the flowmeter system. The calibration factor used here is given by a straight line over the measurement range and results from subtraction of the linear regressions of the experimental points for the case of zero flow. Flow measurements are then corrected by lowering the upstream transit time curves with the calibration factor curve, and the $S^1-L_1-S^1$ transit times are now designated as $t_F - t_T$. Finally, Figs. 12(a) and 12(b) show the relation between times t_T and $t_F - t_T$ for 60% and 100% of maximum flow speed, respectively.

The difference between upstream and downstream transit times can be readily obtained from the latter plots. But in order to highlight the temperature variation during measurements, we transformed the transit time t_T into temperature through the linear relation found between them using either downstream or upstream t_T curve. For this demonstration, we chose the downstream t_T curve. In addition, the difference between upstream and downstream transit time $(t_u - t_d)$ was defined by linear regression rather than using the experimental points, allowing continuous subtraction over the measurement interval. Results are shown in Fig. 13. As expected, the difference in transit time for the intermediate flow is about 60% of that for the maximum flow in the measurement range. Moreover, the linear curves of Fig. 13 have positive inclination since an increase in temperature results in reduction of the ultrasonic velocity c in liquids; accordingly, the difference between upstream and downstream transit times increases, as shown by Eq. (4). Based on the accuracy obtained by the apparatus in the water flow experiment at constant temperature, an error of 1 ns for the difference in transit times was estimated. In future investigations, the flowmeter here designed is intended to be used in flow speed measurements of different industrial fluids and may also be modified into a Doppler-type flowmeter to measure mul-

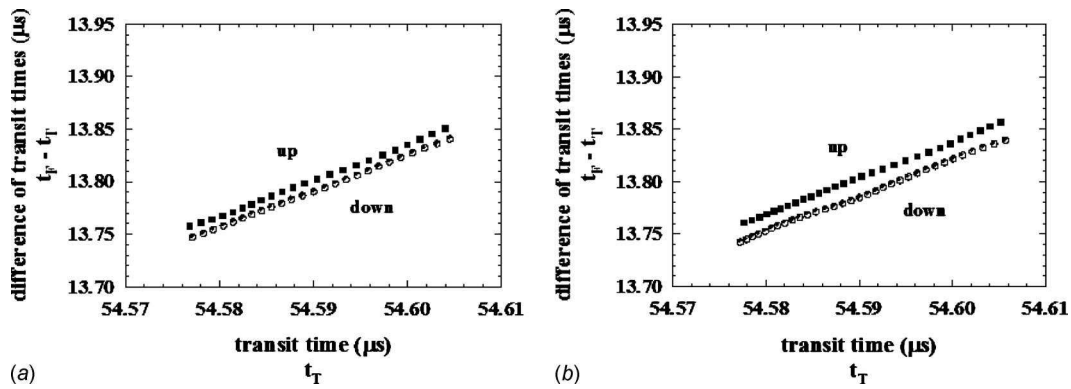


Fig. 12 Downstream and upstream transit time measurements after applying the calibration factor for correcting differences of downstream and upstream transit times at zero flow speed. (a) 60% of maximum flow speed. (b) 100% of maximum flow speed.

tiphase flows, such as bubbles and cavitating structures. As a final remark, it is worth mentioning that although experiments have been carried out at temperatures near 130°C, the steel CBRs can properly operate at temperatures up to 960°C [26].

6 Conclusion

A contrapropagating ultrasonic flowmeter employing steel CBRs was designed for operation at temperatures higher than 100°C, being immune to temperature variation. This ultrasonic flowmeter is driven by shear wave UTs, which generate longitudinal waves to sense the flow speed through mode conversion at the chamfered probing end of the CBRs.

One pair of steel CBRs and another pair of nonclad steel buffer rods, having both the same lengths and diameters, were assembled in contrapropagating configuration in water, being the probing ends cut at 40 deg. It was demonstrated that the SNR of CBRs was superior to that of nonclad buffer rods even in the through-transmission mode, which is a standard way to operate contrapropagating flowmeters.

Thus, a contrapropagating flowmeter prototype made with steel CBRs was designed for operation with water flow at room temperature. Effects of water flow speeds on the difference between upstream and downstream ultrasonic transit times were measured and compared with theoretical expectations. Good repeatability of measurements and agreement with theory were achieved. An accuracy of 1 ns for the difference between upstream and downstream ultrasonic transit times (which is proportional to flow speed at constant temperature) was reached. Motivated by such

results, a contrapropagating flowmeter was then designed and installed in a heater machine for flow speed measurements of hot oil (Thermia-C) at temperatures near 130°C. It was shown that these CBRs could generate specific ultrasonic signals to be used in temperature calibration of flowmeters, allowing temperature variation while still measuring accurately the flow speed. For a 3°C temperature range, the difference between upstream and downstream ultrasonic transit times was measured within 1 ns accuracy (this is the accuracy claimed in the water flow measurement at constant temperature).

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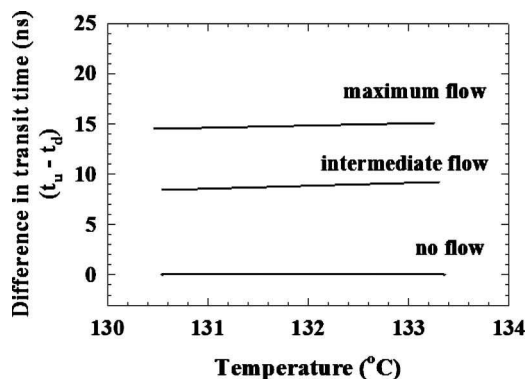


Fig. 13 Experimental results demonstrating the temperature tracking capability of the S^1-S^1 echo for two speeds of hot oil flow. Upstream and downstream transit times can be measured at the same temperature by the apparatus, allowing precise flow speed measurements over the temperature range.

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