NON-INTRUSIVE, ULTRASONIC MEASUREMENT OF FLUID COMPOSITION

Published in the
25th Annual Review of Progress in
Quantitative NDE

eds. D.O. Thompson and D. E. Chimenti
(Plenum, New York, 1998)

INTRODUCTION

With today's increased emphasis on product quality and environmental concerns, the operators of industrial processes need better tools to monitor their process and waste streams [1]. Once these fluid streams are designed and in place, however, it is often difficult and costly to install new monitoring devices, especially if installation would require the shutdown of a critical part of the production process. In addition, operators may not know the best location to monitor the composition of the fluids - it may be required in the process at several points. There is an industry need for a sensitive monitor of fluid streams that can be easily and economically installed and maintained without process interruption [2].

A new ultrasonic technology has been developed which monitors the composition of fluid mixtures from the outside of the pipe or vessel. On-line information is provided about the fluid composition for both product quality assurance and process improvement. Due to the non-intrusive design, installation is easy and does not require cutting the pipe. Two sensor assemblies are simply clamped to opposite sides of the process pipe, and sensor cables are run to the electronics unit. Once the sensors are calibrated for one location, they can be moved and the measurement technique can be applied at many locations.

The ultrasonic contamination monitor has been tested and proven for several applications within the petroleum and chemical industries [3]. This paper describes the measurement technique and the experimental system developed to test the technique in the field. Two different field experiments are described, both intended for application in the petrochemical industries.

FLUID COMPOSITION MEASUREMENT TECHNIQUE

The basic ultrasonic technology is illustrated in Figure 1. Two ultrasonic sensors are attached to the outside of a process pipe or vessel containing a fluid mixture. The mixture is composed of a continuous phase, and another liquid or solid material dispersed within the continuous phase. Each component material has a characteristic density and sound speed [4]. Ultrasonic waves are transmitted by an ultrasonic transducer on one side of the pipe. The waves then travel through the pipe walls and the fluid mixture and are received on the opposite side of the container by a receiving ultrasonic transducer.

Measurements of the ultrasonic propagation though the mixture are used to determine the volume ratio ϕ of the two phases. Volume conservation and mixing laws for density and compressibility can be used to derive the following expression for the change in ultrasonic velocity in the mixture as a function of volume ratio ϕ of the dispersed component [5]:

$$(V/V_c)^{-2} = [1-\phi\,(1-\rho_d/\rho_c)]*[\,1-\phi(1-\rho_c V_c^2/\rho_d V_d^2)] \qquad (1)$$

V_c and V_d are the velocity of the continuous and dispersed phases, respectively. Similarly, ρ_c and ρ_d are the densities of the two phases.

This equation can be rewritten to give an expression for ϕ as a function of the measured velocity V and the velocities and densities of the components. This expression can be used to measure the component ratio for a binary mixture. Because the ratio is determined from sonic properties of the fluid components, it will be sensitive to density and compressibility differences [6]. Even if the two components have the same density, the ratio can be measured due to compressibility differences.

In practice, the time-of-flight (TOF) of the ultrasonic waves is measured, not the velocity. For a fixed travel distance D in the fluid, the TOF is related to velocity as:

$$TOF = D / V \qquad (2)$$

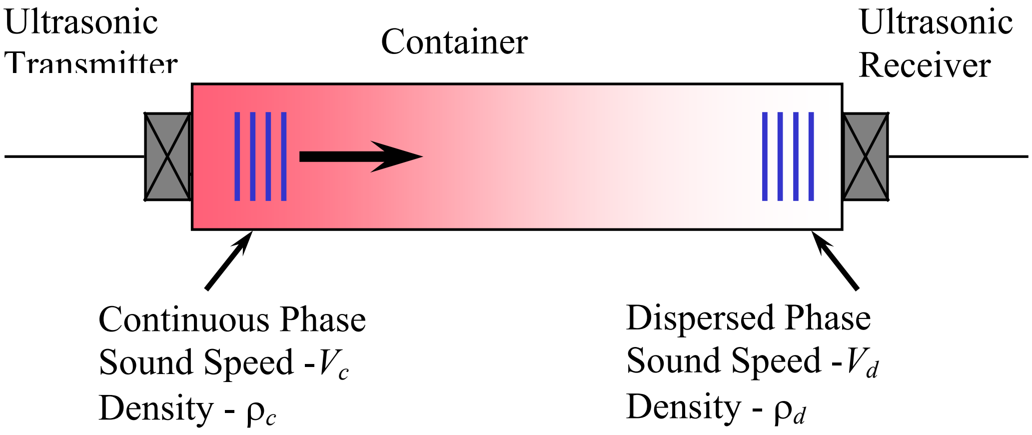

Figure 1. Ultrasonic technique

Although Equation 1 shows a complex dependence of velocity (or TOF) on ϕ, the dependence is often almost linear over practical ranges in component ratio. Since the velocity in both phases is also dependent on their temperature, this must also be measured and compensated for.

Figure 2 shows an example of the nearly linear dependence of the TOF on the component ratio and temperature for a polystyrene polymer fluid. In this case, the dispersed component is the polymerized solid particles, which are mixed in with the styrene monomer continuous phase. As shown in this figure, the TOF is a linear function of the solids content over a 10 percent change in solids. The dependence allows us to use a simple model for the component ratio as a function of TOF and Temperature.

The technique provides a measurement of the physical properties of the mixture, not a chemical analysis. There is no identification of chemical species in the mixture. However, for many applications, the materials in the pipe or vessel are known, and only a measurement of the component ratios is needed.

FLUID COMPOSITION IN PRACTICE

In many situations the ultrasonic properties of the component fluids are unknown. These properties can be determined in the laboratory, and equation (1) is then used to

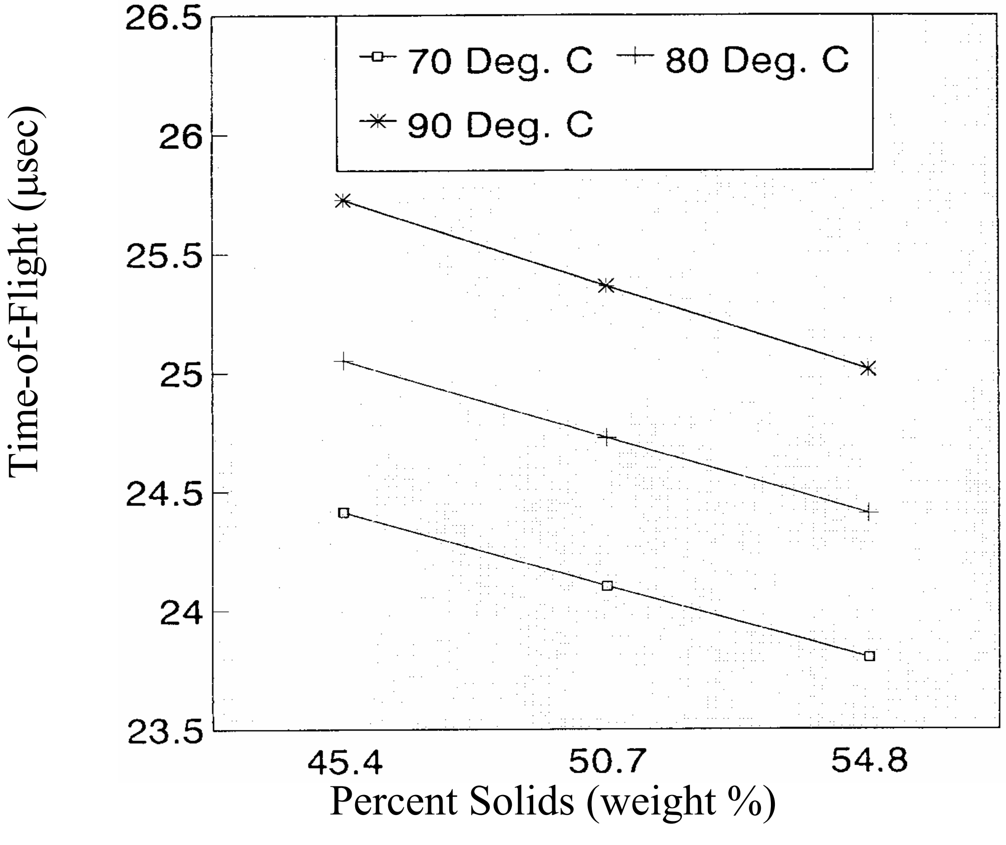

Figure 2. Time-of-flight in polystyrene inside a 1 inch pipe.

measure the component ratios from ultrasonic measurements. Alternatively, an empirical approach can be more practical for on-line applications. The component ratio is expressed as a function of the measured TOF and temperature:

$$\phi = K_0 + K_1{*}TOF + K_2{*}T + K_3{*}TOF^2 + K_4{*}T^2 \qquad (3)$$

where TOF = sonic transit-time reading (~ 1/V)
T = measured temperature
$K_0 ... K_5$ = calibration coefficients obtained from regression analysis.

Once the calibration coefficients are known, the fluid composition is calculated continuously from the TOF and temperature measurements. The calibration technique is performed on line as the fluid moves through the pipe or vessel of interest. Once the sensors are attached to the pipe (see Figure 1.) the following procedure is used to obtain the coefficients:

1. Take fluid samples from a port near the sensors.
2. Record TOF and temperature at the time of sampling.
3. Determine the component fraction ϕ by lab analysis.
4. Perform multiple regression against the sample and sensor readings to get $K_0 ... K_5$.

The calibration coefficients and sensor readings are used to provide continuous fluid composition information. The sensors can be left in place or moved to another location on the same line. Information on fluid composition can be obtained at multiple process locations without ever cutting the pipe.

EXPERIMENTAL SYSTEM

A diagram of the experimental system is shown in Figure 3. This system was constructed to demonstrate the ultrasonic TOF technique in a processing plant environment. The two ultrasonic sensors are fastened to the outside of the pipe or vessel containing the fluids. The two sensors transmit and receive ultrasonic signals that have passed through the pipe walls and the contained fluid. An example of the received ultrasonic waveform is shown at the top of Figure 3. The TOF electronics measure the time from the beginning transmission of the ultrasonic wave to the first arrival of the received ultrasonic wave. The measured TOF and process temperatures are recorded by the system computer, and used with equation 3 to continuously provide fluid composition measurements. These readings can be sent to a control room for operator display and alarm-handling.

A typical sensor mounting arrangement for attachment to a pipe is illustrated in Figure 4. These rugged, saddle block mounts are suitable for an industrial environment, and are adjustable for a wide variety of processes, pipe sizes and conditions. Once the system is calibrated at one location on a pipe, the strap-on bands can be loosened, and the sensors relocated to a different location.

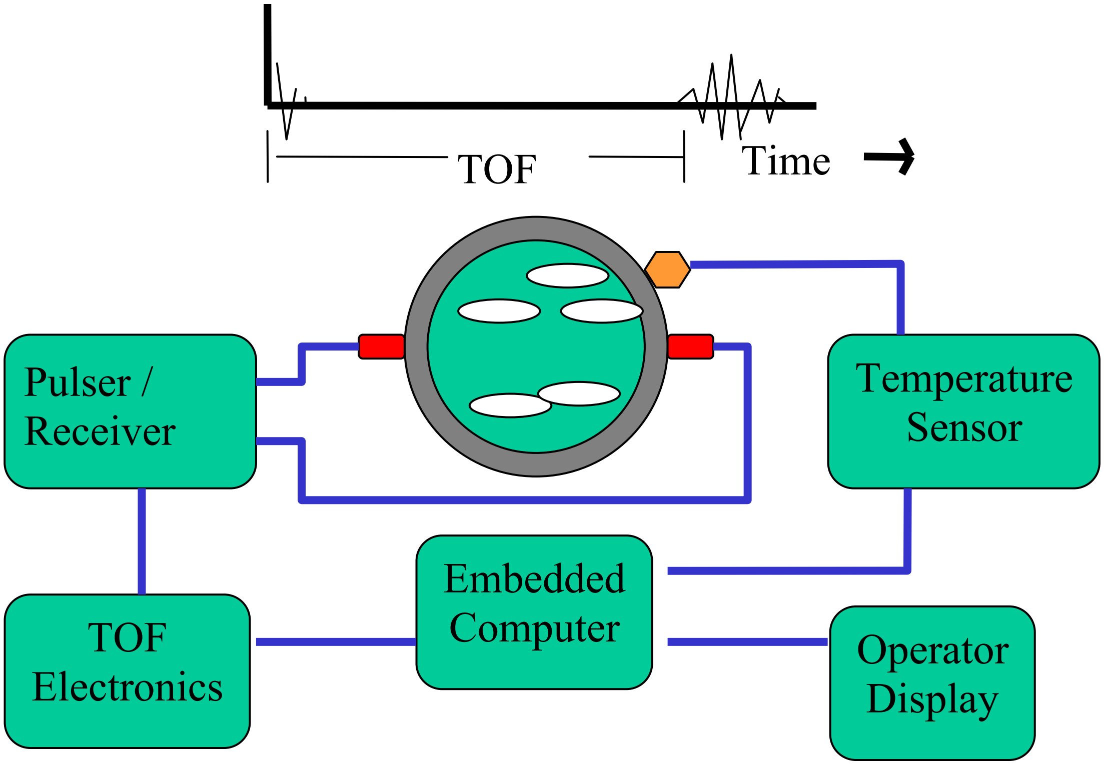

Figure 3. Experimental system.

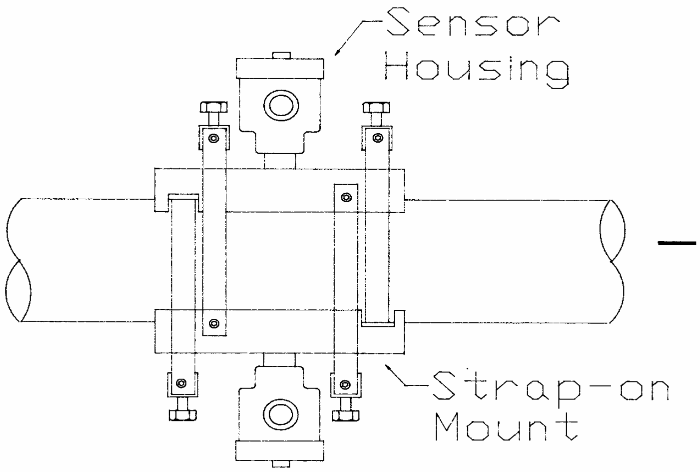

Figure 4. Sensor pipe mount.

FIELD EXPERIMENT #1: OIL-IN-WATER MEASUREMENT

The ultrasonic composition technique has been field tested for several applications within the petroleum and chemicals industries. In one application, an oil production facility needed to monitor the efficiency of a large, 120 foot long separation vessel. Operations personnel suspected that excess crude oil was being drawn into the water outlet of the separator, complicating additional separation further downstream. This resulted in a more costly, energy consuming operation. No oil-in-water meter existed on the water line, and installation would have required a costly shutdown. To test the experiment system for this application, it was strapped to the outside of the 10 inch diameter water outlet pipe at the bottom of the separator, as shown in Figure 5. The non-intrusive design of the monitor made installation easy, and did not require a shutdown of operations.

The continuous oil composition readings from the ultrasonic system are shown in Figure 6. The ultrasonic system was calibrated by taking fluid samples from a tap downstream of the sensor location. These samples were analyzed in the laboratory and the results were used to calibrate the system using the procedure described above. The laboratory measurements of the oil samples taken from the water stream are shown as the dark squares. The ultrasonic composition measurements agree well with the results of spinout tests of additional samples taken from the stream. The spinout readings are obtained by using a centrifuge to separate the oil from the mixture and manually reading the oil concentration.

The ultrasonic technique provided real-time, continuous composition information, which allowed the operators to identify a problem with the water valve control system. The on-line measurements confirmed that excessive oil was being drawn into the water leg at repetitive intervals due to the formation of a vortex in the separator. The large swings in water quality shown in Figure 6 were due to improper control of the water dump valve. These field tests gave the operators the information needed to better control the valve and improve water quality.

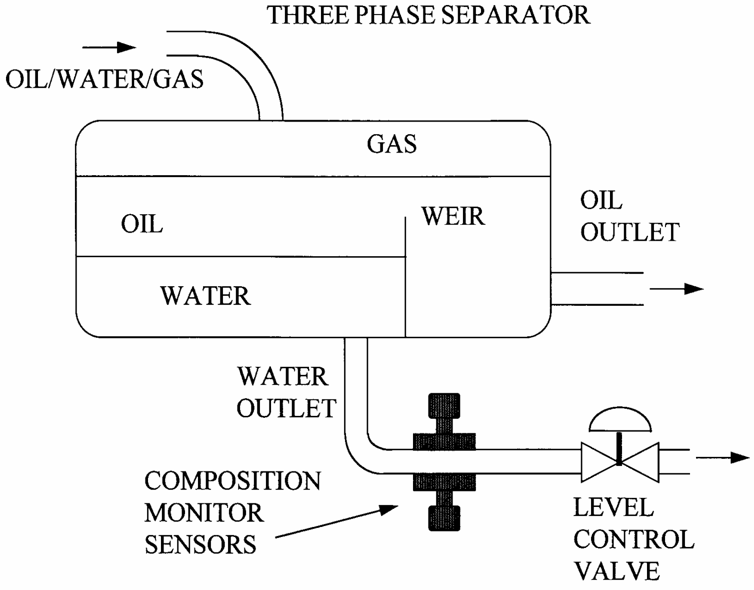

Figure 5. Oil-in-water process measurement.

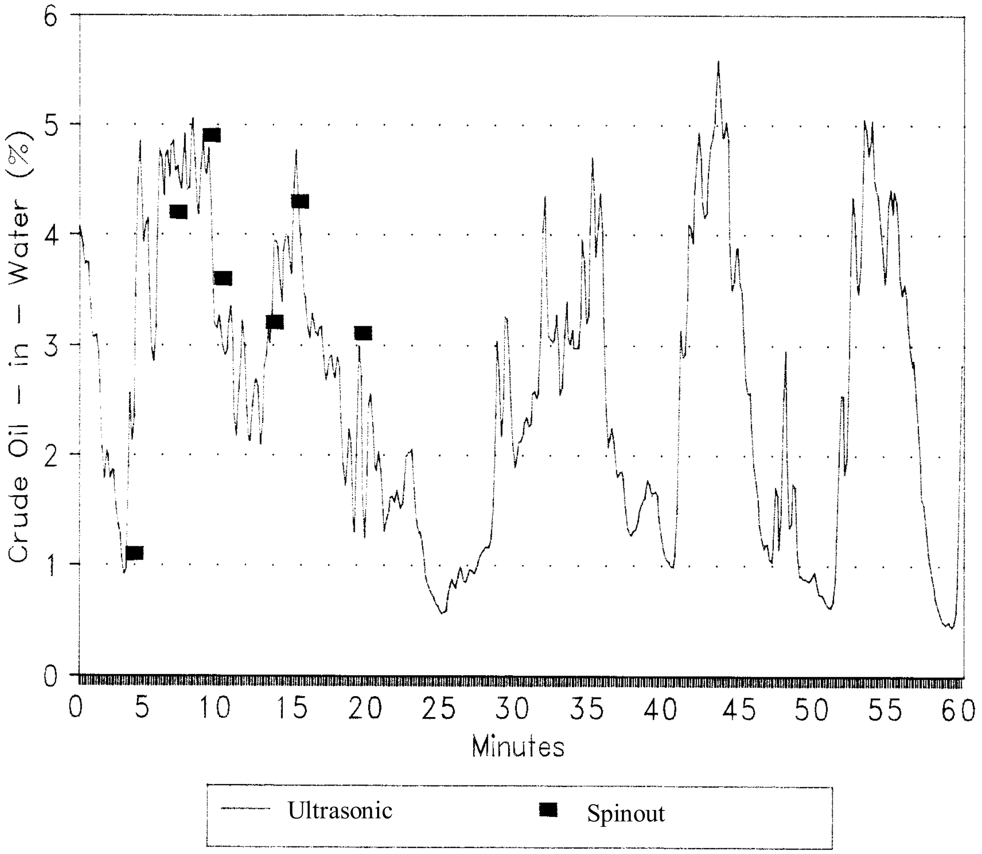

Figure 6. On-line oil-in-water measurements.

FIELD TEST #2: POLYMERIZATION RATE CONTROL

The ultrasonic technique has also been successfully field tested in the production plant of a major plastic manufacturer. The instrument is used to accurately measure the amount of residual monomer left in the manufactured polymer after the polymerization reaction. The residual monomer is the primary quality control parameter for this plastic material [7]. Before the prototype monitor was available, samples of the polymer were drawn off and analyzed in a laboratory every 2 hours. The long delays in sample analysis and lack of confidence in the sample readings resulted in poor control of the reaction process [8]. With the on-line ultrasonic monitor, the operators get a new reading every 20 seconds, enabling real-time reactor heating adjustments. The quality control for the produced polymer has been increased substantially due to the timely information provided by the monitor. The accuracy of the monitor readings has been determined to be as good as or better than the laboratory analysis (0.2% solids by weight), yet it provides instant information, rather than requiring the long delays.

DISCUSSION

An ultrasonic technique has been developed which provides non-intrusive, continuous measurements of fluid composition. Due to the non-intrusive design, the sensors never come in contact with the process fluids. The sonic sensors can be installed without modifying piping, disrupting operations, or installing sample-conditioning equipment. The sensitivity of the sonic technology depends on the size of the pipe carrying the process fluid. Larger pipes have a longer path for the sound waves, increasing sensitivity to changes in the fluid. For most processes with pipes or vessels larger than a few inches in diameter, an accuracy of 0.1% can be achieved.

The technology can be used for any process where the purity of a fluid stream needs to be monitored to optimize operations or ensure quality. The only requirement is that the fluid must carry the ultrasonic wave without severe attenuation, which would be caused by large amounts of gas bubbles. The non-contact technology is particularly useful for applications in difficult environments such as corrosive materials or severe temperatures.

This paper reports on several successful field experiments that demonstrate the usefulness of the technique for on-line process monitoring. Extensive field tests confirm that the ultrasonics can provide a movable sensor for detecting oil/water emulsion problems in separator control systems. In addition, the ultrasonic technique is the first known, non-fouling technique for polymerization rate control in large capacity polymer manufacturing.

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