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Liquid Film Thickness Measurement by An Ultrasonic Pulse Echo Method

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초음파 Pulse-echo 방법에 의한 액체막 두께 측정

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Abstract

The main purpose of this work is to investigate the effects of the wall thickness, the ultrasonic frequency, and the acoustic impedance of wall material on the liquid-film thickness measurement by an ultrasonic pulse echo method. A series of liquid-film thickness measurements in a horizontal air-water stratified system was performed employing a plate-type and a tube-type test sections. Measurements were repeated changing (1) the wall thickness of the test section and (2) the transducer frequency. Also, in an effort to improve the accuracy of the measurement and to examine the effect of acoustic impedance of wall material on the measurement by an ultrasonic technique, two different stand-off rods, one made of stainless steel and the other polyacrylate, were used in the liquid-film thickness measurement. These experimental results are discussed and compared with the actual film thicknesses.

요약

경수형 원자로의 운전과 안전성 해석을 위해 열수력학적 모형을 개발하는 것이 하나의 중요한 과제이다. 특히, 2상류의 열수력학적 모형을 개발하기 위해서는 기포율, 액체막 두께, 유동 영역과 같은 중요한 변수들을 실제로 측정한 값이 필요하다.

본 연구의 목적은 초음파 Pulse-echo 방법을 이용하여 액체막 두께를 실험적으로 측정하고, 이론치와 비교 분석하여 (1) 관벽의 두께, (2) 초음파의 주파수, (3) 관벽의 재질 등이 액체막 두께 측정에 미치는 영향을 분석하는 데에 있다.

평판형 (Plate-type)과 관 (Tube-type) 으로 된 시험관을 이용하여 수평으로 놓인 물-공기의 층류계 (a horizontal airwater stratified system)를 만들어 일련의 액체막 두께 측정 실험을 수행하였다.

시험관의 벽 두께와 초음파 Pulse-echo 의 주파수를 변화시키면서 액체막 두께 측정을 반복하였다. 또한, 관벽의 acoustic impedance 가 초음파 Pulse-echo 방법으로 액체막 두께를측정할 때, 어떠한 영향을 주는가도 아울러 파악하기 위해서 스텐레스 강과 폴리아크릴 (Polyacrylate) 등 재질이 다른 두 개의 격리봉 (Standoff rod) 을 사용하여 액체막 두께를 측정하였다. 이렇게 하여 얻은 실험 결과를 제시하고 실제로 측정한 액체막 두께와 비교 분석하였다.

Nomenclature

A	; cross-sectional area of the plate-type test section
D	; inside diameter of the tube
f	; frequency of ultrasonic wave
L	; length of the tube
N	; number of cycles in an ultrasonic pulse
P_i	; incident wave sound pressure
P_r	; reflected wave sound pressure
P_t	; transmitted wave sound pressure
Δt	; measured transit time through liquid film
v_l	; sound velocity in the liquid film
v_w	; speed of ultrasonic wave in the wall material
V	; volume of water in the test section
Z_s	; acoustic impedance of the stainless steel
Z_w	; acoustic impedance of the water
δ_m	; measured water film thickness using the ultrasonic pulse-echo method
δ_{th}	; theoretical water film thickness
δ_w	; actual thickness of the plate (or tube wall)
$\delta_{w,min}$	; minimum wall thickness of the plate (or tube) that will not result in the superposition of echoes
θ	; angle that can be obtained from Eq. (3 a)
λ	; ultrasonic wavelength

1. Introduction

Thermohydraulic modeling of a two-phase flow is an important task for nuclear reactor designers and safety analysists. In the thermohydraulic analysis and modeling of a two-phase flow, several important parameters such as void fraction, liquid-film thickness, and flow regimes are required. This paper is concerned with the parametric effects on the liquid film thickness measurements by an ultrasonic pulse-echo method. Liquid films occur in many situations. For instance, in annular two-phase flow, part of the liquid phase flows as a film on the channel wall. Measurement of the thickness of this film is important in developing models for annular flow. Film thickness measurements are also important in such applications as filmwise mass transfer equipment, engine manifolds, etc (1). The basic methodology of this technique has previously been investigated by Starkovich et al. (2) Dallman (3), and Chang et al. (4).

Various techniques of liquid-film thickness measurement that have been developed since 1960's are (5): (1) needle contact method, (2) film admittance method, (3) fluorescence method, and (4) X-ray absorption method. Each of these methods, however, has some inherent drawbacks to be applicable to the high pressure metallic pipe flow such as nuclear reactor coolant systems.

Advantages of the ultrasonic pulse-echo method over the above existing methods include: (1) a nondestructive method, (2) faster response time, (3) straight forward calibration, (4) real time data acquisition, and (5) less sensitive to temperature.

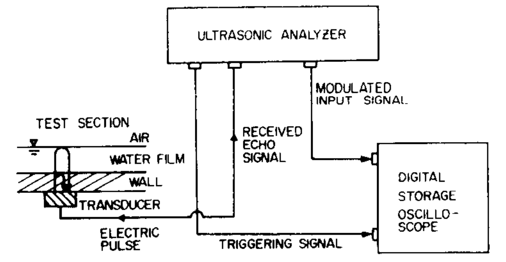
In the present work, the effects of wall thickness, wall material, and ultrasonic frequency on the measurement are investigated. Also, in an effort to improve the accuracy of the liquid-film thickness measurement by an ultrasonic technique, the method of using a stand-off rod used by Starkovich et al. (2) is examined.

II. Principle and Measurement System

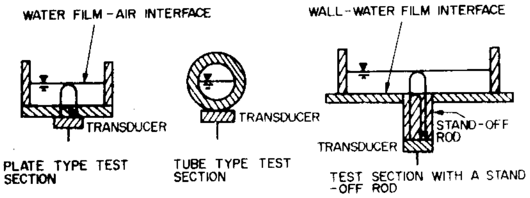
1. Principle of Ultrasonic Pulse Echo Method

The liquid film in the stratified or annular two-phase flow can be modeled as shown on the left-hand side of Figs. 1 (a) and 1(b). The ultrasonic pulse discharged from the transducer will partly be reflected at the tube wall-liquid interface, and received by the same transducer. The remainder of the pulse will be transmitted through the liquid and then reflected back to the transducer from the liquid film-air interface. The reflected signal received by the transducer can be plotted as a function of time using an oscilloscope as shown in Fig. 2. The transit time of ultrasonic wave passing through the liquid film, Δt, can be determind by the difference between the initial wall-liquid film interface echo and the liquid film-air interface echo. Since the transit time is linearly proportional to the liquid film thickness, the film thickness δ can be calculated from the measurement of the transit time using the following equation.

$$\delta = v_l \Delta t \qquad (1)$$



(a) ULTRASONIC FILM THICKNESS MEASUREMENT SYSTEM



(b) TEST SECTION TYPES

Fig. 1. Ultrasonic Liquid Film Thickness Measurement System and Test Section Geometries

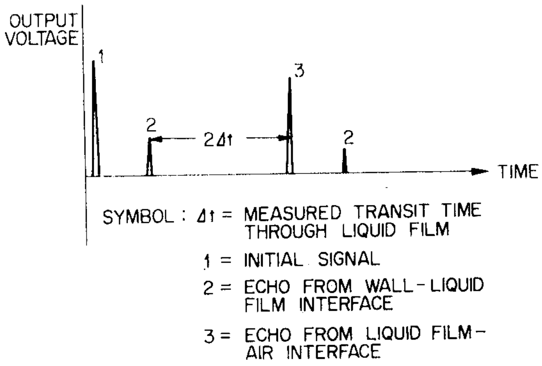


Fig. 2. Schematic of Ideal Ultrasonic Echo Waveform for the Liquid Film Thickness Measurement

2. Experimental Apparatus and Test Parameters

A schematic diagram of the single pulse ultrasonic liquid film thickness measurement system along with the test section geometries is shown in Fig. 1. The experimental apparatus consists of (1) ultrasonic analyzer, (2) digital storage oscilloscope, (3) ultrasonic transducer, and (4) various type of test sections.

The electronic pulse is generated by an ultrasonic analyzer (Panametrics model 5052 UA), and then converted into ultrasonic pulse in ultrasonic transducer.

The ultrasonic transducer (Panametrics normal contact type transducer) discharges ultrasonic pulse to a test section and receives the reflected echo waves. The echo signal received by the same transducer is handled by the ultrasonic analyzer, and the result is displayed on the digital storage oscilloscope (Nicolet series 2090) that has 20 MHz sampling rate.

Test parameters used in the "study of various parametric effects on the liquid film thickness measurement by an ultrasonic method" are summarized and shown in Table 1.

Table 1. Test Section Dimensions and Test Parameters

(a) Test Section Dimensions

Test Section Geometry	Typical Dimensions (mm)
(1) Plate-type (Wall Thickness × Width × Length):	8.36 × 81.25 × 101.65
(2) Tube-type (Wall Thickness × ID × Length):	5.20 × 42.61 × 199.52

(b) Test Parameters and Test Conditions

Test Parameters	Range of Parameters	Test Section and Other Conditions Used
(1) Wall Thickness (mm)	(A) 3.87(Acryllic Resin) (B) 3.00(Acryllic Resin) (C) 2.00(Acryllic Resin) (D) 1.40(Acryllic Resin)	(1) Four plate-type test sections with different wall thickness (2) Transducer frequency: 2.25MHz (3) Wall Material: Acryllic Resin
(2) Transducer Frequency (MHz)	(A) 1.0 (Acryllic Resin) (B) 2.25(Acryllic Resin)	(1) Plate-type test section with wall thickness of 1.40mm (2) Wall Material: Acryllic Resin
(3) Wall Material (Acoustic Impedance Ton/cm^2-sec)	(A) Stainless Steel 302 (4.55) (B) Acryllic Resin(0.32)	(1) Plate-type with Stand-off Rod (2) Stand-off Rod length: 50mm (3) Transducer Frequency: 2.25MHz

III. Experimental Results and Discussion

1. Water Film Thickness Measurement for a Plate-Type Test Section

The thickness, width, and length of the plate-type test section (made of acryllic resin) used for this test series are 8.36mm, 81.25mm, and 101.65mm, respectively. The transducer frequency, on the other hand, was set at 2.25MHz.

As shown in Table 2, a series of experiments were conducted at various water film thickness: water film thickness was varied by changing the volume of water in the test section shown in Fig. 1(b). Typical ultrasonic waveforms corresponding to water film-air stratified flow through a duct (under static condition) are shown in Fig. 3. Fig. 3 shows that the amplitude of the echo decays exponentially; however, it is possible to determine the liquid film thickness either from the first set of reflected signals or from the second (or third) set of reflected signals. As Chang et al.(4) have already shown, there is no difference in Δt's measured from the first, second, and third sets of reflected signals.

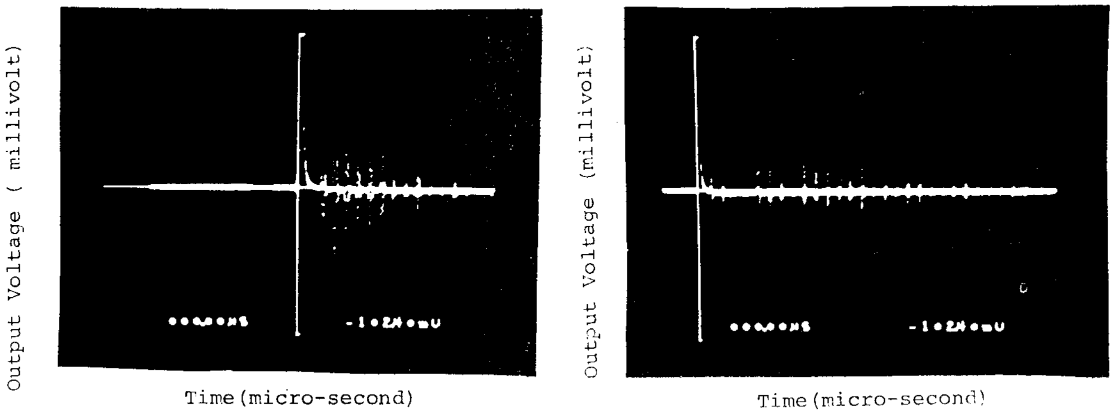
Table 2. Results of the Test with a Plate-type Test Section

Water volume, cc	δ_{th}, (mm)	δ_m, (mm)	Absolute Error (mm)
20	2.42	2.34	0.08
30	3.63	3.61	0.02
40	4.84	4.83	0.01
50	6.06	5.95	0.11
60	7.27	7.21	0.06
70	8.48	8.40	0.08
80	9.69	9.63	0.06
90	10.90	10.82	0.08
100	12.11	12.04	0.07
150	18.17	18.14	0.03

The results of the water-film thickness measurements in stratified water-air system(in plate-type test section), using the first set of reflected signals, are summarized in Table 2. The theoretical thicknesses shown in Table 2 are obtained from the following relationship:

$$\delta_{th}=\frac{V}{A} \tag{2}$$

The error of the detection system is estimated to be roughly ±0.07mm in 22°C water, whereas the error of the measurement of water volume with 0.1cm^3 grading pipet tube is about



A) Thin film (20cc) B) Thick film (150cc)

Fig. 3. Typical Ultrasonic Echo Wave Forms Corresponding to Plate Type Test Section

±0.01mm. When these inherent errors of the present detection systems are taken into account, the agreement between the measured values (δ_m) and the actual values (δ_{th}) is extremely good.

2. Water Film Thickness Measurement for a Horizontal Tube-Type Test Section

The ultrasonic echo waveforms, corresponding to air-water stratified flow through 42.61mm I.D., 5.20mm thick, and 199.52mm long horizontal single tube (polyacrylate resin), were similar to those of Fig. 3 except for the reduced amplitude of echoes. The transducer frequency used for this test was also 2.25MHz.

The results of water film thickness measurements in stratified air-water system in polyacrylate resin tube-type test section are summarized in Table 3 along with the theoretical thickness. The theoretical thickness in the tube-type test section was evaluated from the following equation:

$$\delta_{th}=\frac{D}{2}(1+\cos\theta) \qquad (3)$$

where θ can be obtained from the following correlation:

$$\sin2\theta-2\theta=\frac{8}{D^2}\left(\frac{V}{L}-\frac{\pi}{4}D^2\right) \qquad (3a)$$

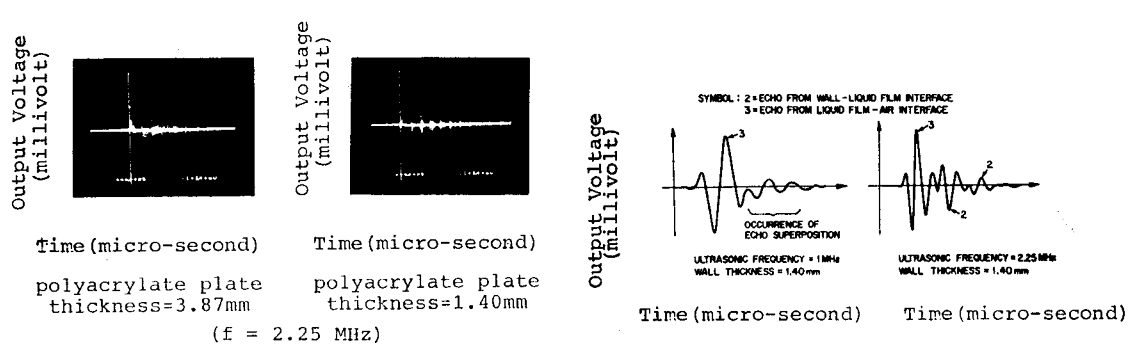
From Table 3 one can observe in general, that there is a good agreement between δ_m and δ_{th}; the discrepancy between the measured thickness δ_m and the theoretical thickness δ_{th} increases with decrease in the water film thickness. This error is due to the relatively large effect of the meniscus, induced by the surface tension, for thin water film in the calculation of the theoretical thickness.

Table 3. Results of the Test with a Tube-Type Test Section

Water volume, cc	δ_{th}, mm	δ_m, mm	Absolute Error, mm
10	3.26	3.75	0.49
15	4.30	4.91	0.61
20	5.23	5.65	0.42
30	6.92	7.29	0.37
40	8.45	8.70	0.25
50	9.88	10.04	0.16
60	11.24	11.34	0.10
70	12.55	12.60	0.05
80	13.83	13.83	0.00
90	15.07	15.09	0.02

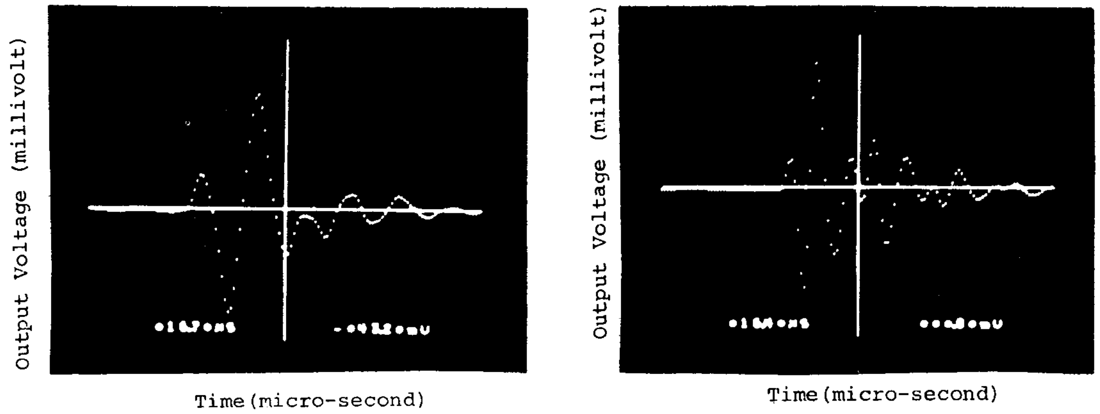
3. Effects of Wall Thickness and Frequency

Since there are a few cycles in a single ultrasonic pulse due to inherent characteristics of the detection system, superposition of successive ultrasonic echoes can occur when the tube wall is very thin. To examine this effect, four different test sections made of acrylate plate (whose wall thicknesses are 3.87, 3.00, 2.00 and 1.40 mm, respectively) are tested at two different transducer frequencies of 1. and 2.25MHz. As



(a) Effect of Wall Thickness (b) Effect of Transducer Frequency

Fig. 4. Effects of Wall Thickness and Transducer Frequency



a) 1.0MHz b) 2.25MHz

Fig. 5. Variation of Detailed Single Ultrasonic Echo Wave Set Depending on the Ultrasonic Transducer Frequency

can be seen in Fig. 4(a), the time interval between adjacent echoes becomes shorter as the wall thickness decreases. When the plate thickness of 1.40 mm was tested at the transducer frequency of 1MHz, it was impossible to locate the peak position of individual echo due to superposition of successive echo waves as can be noted in Fig. 4(b). Inferring from this result and theoretical analysis of echo waveforms, the following relationship can be derived for the minimum wall thickness that will not result in the superposition of echoes. Since the superposition of echoes begins when $2\delta_{w,min}=N\lambda$,

$$\delta_{w,min}\geq\frac{Nv_w}{2f} \tag{4}$$

where N is the number of cycles in one ultrasonic pulse and v_w(Km/sec) is the speed of ultrasonic wave in the wall material, and f(MHz) is the frequency of ultrasonic wave.

The schematic diagrams of Fig. 4(b) show the main characteristics of Fig. 5. Fig. 5. is the result of the test with a polyacrylate plate of 1.40mm in thickness: each of these figures shows the wave forms of three successive echoes corresponding to the ultrasonic transducer frequencies of 1.0 and 2.25 MHz, respectively.

The minimum wall thickness, $\delta_{w,min}$, that will not result in the superposition of echoes for polyacrylate plate at the transducer frequencies of 1.0 and 2.25MHz are:

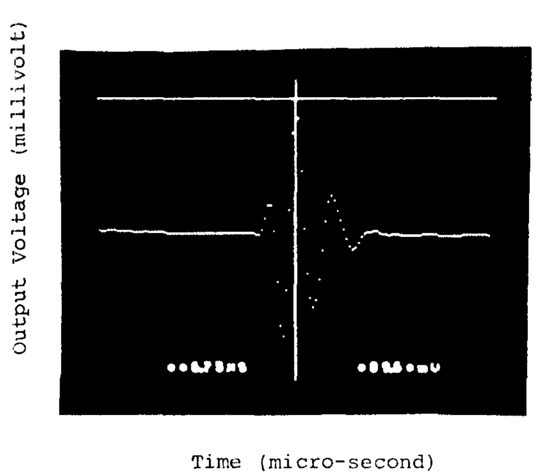


Fig. 6. The First Echo Shape on the Oscilloscope for Polyacrylate Plate ($f=2.25$ MHz)

$$\delta_{w,\min}\geq 4\text{mm (when } f=1\text{MHz)} \qquad (5)$$

$$\delta_{w,\min}\geq 1.78\text{mm (when } f=2.25\text{MHz)} \qquad (6)$$

The above $\delta_{w,\min}$ values are calculated from Eq. (4) using $v_w=2.67$km/sec and $N=3$ (obtained from Fig. 6).

Notice that when $f=1$MHz $\delta_{w,\min}$ should be far greater than the polyacrylate plate thickness ($\delta_w=1.40$mm) used in the test; therefore, we would expect that there will be superpositions of echoes for this case. On the other hand, when $f=2.25$MHz $\delta_{w,\min}$ is slightly thicker than $\delta_w=1.40$mm, and a slight superposition is expected.

As can be seen in Fig. 5(a) and illustrated in Fig. 4(b) (the first figure from the left), clearly there are superpositions of echoes, whereas Fig. 5(b) and Fig. 4(b) (the second figure from the left) show that there is a slight superposition of echoes at both ends. This is in complete agreement with the above predictions. This result also shows that the higher ultrasonic transducer frequency gives a better resolution for a given tube (or plate) material and wall thickness.

For application of ultrasonic liquid film thickness measurement technique to a thinner wall than the one given by the above Eq. (4), the stand-off rod technique shown in Fig. 1(b) and used by Starkovich et al. (2) may be employed.

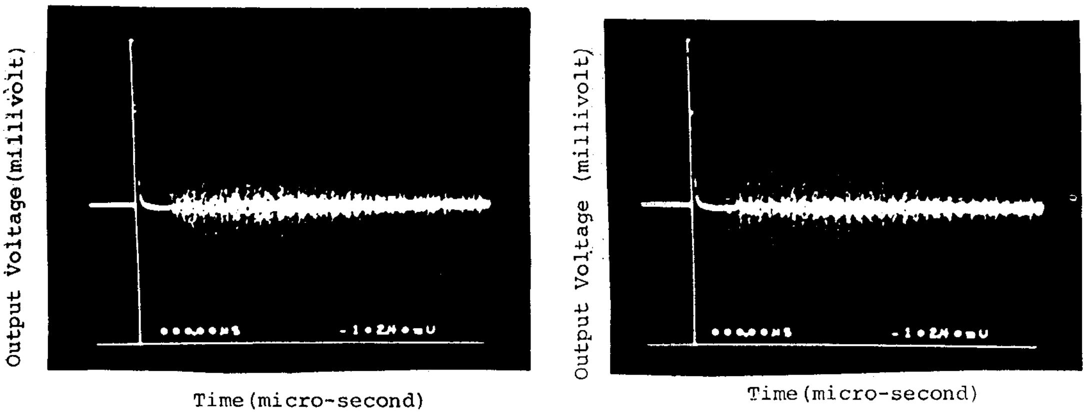
4. Effects of Acoustic Impedance of Wall Material

The acoustic impedance matching is another important factor in ultrasonic technique. If the acoustic impedance of the wall material is much larger than that of water, the acoustic pressure transmitted to the water film will be reduced appreciably after passing through the tube wall (5). As a result, the echo from the liquid film-air interface may become so weak that the peak point of echo may no longer be distinguishable. To observe this phenomena and the effect of wall material on the liquid film thickness measurement by an ultrasonic method,two stand-off rods, one made of stainless steel and the other polyacrylate, are examined.

The acoustic impedance ratio of stainless steel and water and that of polyacrylate and water are 31 to 1 and 2 to 1, respectively. Figs. 7(a) and 7(b) are the ultrasonic echo wave forms corresponding to the high acoustic impedance wall (i.e., stainless steel standoff rod) with and without the presence of water film on top of the wall: it can be observed that the amplitude of echo from the water film/air interface (Fig. 7b) is aoubt one-eighth of that from the wall/water film interface.

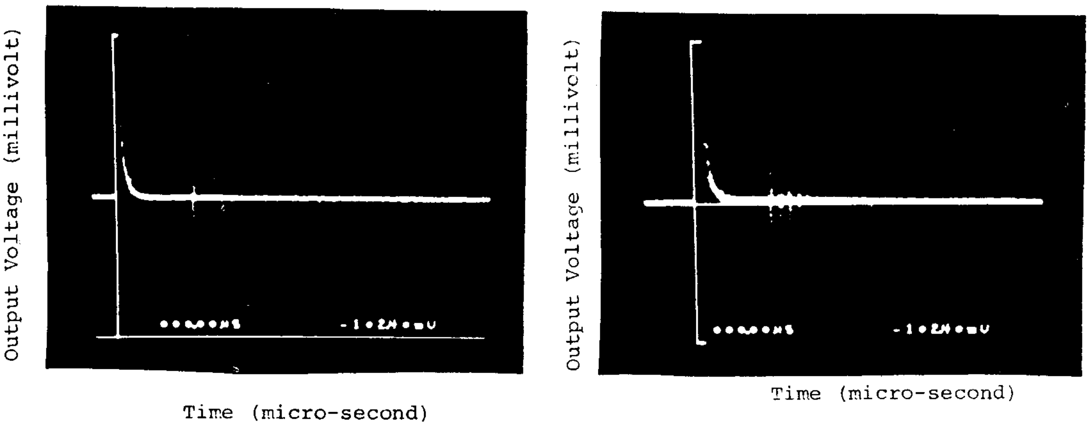
Figs. 8(a) and 8(b), on the other hand, corresponds to the case of a low acoustic impedance wall (i.e., polyacrylate): these two figures show that the amplitude of the echo from the water film/air interface (Fig. 8b) is far greater than that of the wall/water film interface (Fig. 8a).

A close examination of the two figures shown in Fig. 7 reveals that there is an extra small amplitude of echo (about 1/8 of the largest) between the first and the second largest amplitude of echoes in Fig. 7(b), whereas none can be found in Fig. 7(a): this echo is the reflected



a) without liquid film b) with liquid film

Fig. 7. Ultrasonic Echo Wave Forms Corresponding to Stainless Steel Stand-off Rod With and Without Water Film



a) without liquid films b) with liquid films

Fig. 8. Ultrasonic Echo Wave Forms Corresponding to Acrylic Resin Stand-off Rod With and Without Water Film

wave from the water film/air interface. The ratios of the sound pressures of the reflected and the tranmitted waves to the pressure of the incident wave, on the steel/water and water/steel interface, are given by the following equations (6).

On the steel/water interface (i.e., if the wave coming from steel strikes water),

$$\frac{P_r}{P_i}=\frac{Z_w-Z_s}{Z_w+Z_s}=-0.937 \qquad (7)$$

$$\frac{P_t}{P_i}=\frac{P_i+P_r}{P_i}=\frac{2Z_w}{Z_w+Z_s}=0.063 \qquad (8)$$

On the water/steel interface (i.e., if the wave coming from water strikes steel),

$$\frac{P_r}{P_i}=\frac{Z_s-Z_w}{Z_w+Z_s}=0.937 \qquad (9)$$

$$\frac{P_t}{P_i}=\frac{P_i+P_r}{P_i}=1.937 \qquad (10)$$

The negative sign indicates the reversal of the phase relative to the incident wave. In the above equations $Z_w=0.148$ (at 20°C) and $Z_s=4.55\ 10^6$g/cm^2-sec have been used (7). If the incident wave sound pressure P_i coming from the stainless steel wall to water is taken as 1, the first echo P_r (the reflected wave sound pressure at the stainless steel/water interface) is 0.937 according to Eq. (7). On the other hand, the reflected wave sound pressure at the water/air interface that is transmitted through water and stainless steel stand-off rod is only one-eighth of the first echo P_r (since $P_t = 1.937 \times P_i = 1.937 \times 0.063 = 0.122$). This confirms what can be observed in Fig. 7).

To improve the resolution for the case of a high acoustic impedance wall, however, a stand-off rod made of a low acoustic impedance material can be employed.

5. Water Film Thickness Measurement Using a Stand-off Rod

Figures 7 and 8 show the ultrasonic echo wave forms corresponding to stainless steel and acryllic resin stand-off rod with and without water film. When Fig. 8 is compared with Fig. 3 it becomes clear that the echo wave forms become simpler when a stand-off rod made of low acoustic impedance material is used. Because of this advantage, water film thickness measurements were also made with a polyacrylate rod serving as a stand-off. The results are summarized in Table 4. Agreement between the measured δ_m and theoretical δ_{th} is also very good.

The use of stand-off rod offers several advantages: (1) wall thickness is not limited, (2) simpler ultrasonic echo wave form can be obtained, and (3) the transducer can be protected from the hot fluid such as the nuclear reactor coolant.

Table 4. Results of the Test with a Stand-off Rod

water volume, cc	δ_{th}, mm	δ_m, mm	absolute error, mm
20	2.44	2.45	0.01
30	3.66	3.68	0.02
40	4.88	4.91	0.03
50	6.10	6.10	0.00
60	7.32	7.29	0.03
70	8.54	8.51	0.03
80	9.76	9.70	0.06
90	10.98	10.97	0.01
100	12.20	12.19	0.01
110	13.41	13.35	0.06

IV. Conclusion

From the present study, it can be concluded that the ultrasonic pulse-echo method can be used to measure liquid film thickness inside a tube when (1) the tube wall thickness is greater than the minimum given by Eq. (4) and (2) when the acoustic impedance of the tube wall is low enough such that the peak point of echo from the liquid film-air interface remains distinguishable. To remove these restrictions in practical application, one may employ a stand-off rod of a low acoustic impedance material.

References

1. Gad Hestroni, "Handbook of Multiphase System; Measurement of Liquid-Film Thickness," McGraw-Hill, 1982.
2. V.S. Starkovich et al., "Ultrasonic Liquid Film Thickness Measurements," Trans. Am. Nucl. Soc., Vol. 35, pp. 640-641, 1980.
3. John C. Dallman, "Application of Ultrasonics to the Measurement of Thin Flowing Liquid Films," Trans. Am. Nucl. Soc., Vol. 39, pp. 1039-1040, 1981.
4. J.S. Chang et al., "Flow Regime Characterization and Liquid Film Thickness Measurement in Horizontal Gas-Liquid Two-Phase Flow by an Ultrasonic Method," Measurements in Polyphase Flow, pp. 7-12, 1982.
5. G.F. Hewitt, "Measurement of Two-Phase Flow Parameters," Academic Press, London, 1978.
6. J. Krauthramer et al., "Ultrasonic Testing of Materials," Springer-Verlag, New York, 1978.
7. Dale Ensminger, "Ultrasonics, the Low and High Intensity Applications," Battelle Columbus Laboratories, 1973.