A FEASIBILITY STUDY OF ULTRASONIC/SONIC
FLOWMETERS FOR COAL SLURRIES

by

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PREFACE

This document is the first in a series of reports on the theoretical feasibility of using acoustic mass flowmeters for the media encountered in demonstration or pilot plants for coal conversion processes. Dense phase, dilute phase and dirty gas media will be considered. This report deals with media having light concentrations of 10 - 30% (dilute phase) by volume of coal. The reports to follow will treat the feasibility of acoustic mass flowmeters for media having heavy concentrations up to 70% (dense phase) by volume of coal and the solid particle-gas (dirty gas) two-phase systems. In the course of the investigation, it may be necessary to consider media that cannot be included in the above general classifications. In that event, additional reports will be issued, as necessary.

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ABSTRACT

An analysis of sonic techniques for flow measurement in coal slurries shows that operation of a transmission type flowmeter is feasible for a range of one meter at a frequency range of 32.5 kHz to 400 kHz and a range of ten centimeters at a frequency range of 325 kHz to 1 MHz using the sonar equation as the measure of performance. Slurries with moderate concentrations of 10 - 30% solids by volume and particle size of 100 microns are assumed. Based on this assumption, the attenuation constant, the transmission loss, the directional gain, the source level and the processing gain for the transmission type flowmeter are determined.

1.0 INTRODUCTION

A recent ANL study ¹ has indicated that sonic/ultrasonic techniques may be applied, in some cases, to the measurement of two-phase flows found in coal conversion processes. The feasibility of the various approaches using active or passive sonic means was discussed to some degree, and a general statement was made based largely on the opinions or experiences of engineers and other people in the industry. The physical arguments, in general, did not include a quantitative analysis of feasibility.

From a systems analysis viewpoint, the establishment of feasibility depends upon providing a measure of effectiveness ². This measure is the criterion by which solutions to a specific physical or engineering problem are to be judged. A good measure of effectiveness,

- measures the system performance
- is quantitative
- is statistically efficient and stable
- is complete
- is simple
- has a physical meaning.

If time and cost are a part of the problem, then the measure must also account for scheduling and funding limitations. The feasibility that we wish to deal with might be called "technical feasibility" since we do not consider, for the present, the time and cost implications.

When considering the performance of a sonic system which uses the generation, transmission, and reception of sound, the most widely used measure of effectiveness is the Figure-of-Merit, derived from the sonar equation, which simply states that, the received signal level equals the noise background level.

The Figure-of-Merit is defined by rearranging the terms in the sonar equation to allow computations of maximum allowable transmission loss. A different form of the sonar equation will be used later in order to allow the computation of noise background level.

This measure is not unique to sound and may be applied to radar, astronomy, and communication theory. The power of the sonar equation which underlies the Figure-of-Merit computation is that it fulfills the criteria of

a good measure of effectiveness. It is a quantitative measure of the system performance regardless of whether that system is active or passive, it is statistically efficient in that RMS values may be used for all random variables, and it is a simple algebraic addition of terms which are identifiable with each separate physical function or process within the system operation sequence.

A full study of all alternative means of sonically measuring flow velocity or mass flow rate for all flowing media found in coal conversion processes is necessary but beyond the scope of the present effort. A general review has already been given in reference 1 and a related study is underway at ANL. Without a full study, the normal procedure is to consider the worst case within a class of systems as was done here.

The media of interest in coal conversion processes vary depending upon which stage of the process is considered. Thus, crushed coal falling from a hopper will produce a compact mixture of solids and gases. A transport line will have a mixture of fluids and solids and a bed within the reactor will have a composition ranging from a porous solid to a fluidized solid-gas mixture. The cyclone separator lines contain gases with dispersed or even trace amounts of particulate solid. When viewed as a system in equilibrium, the flow rate of all gases and solids within the coal conversion cycle must be known so that proper balance and control may be achieved. Progress toward this goal hinges upon the proper characterization of each medium involved. A start toward this end was made in reference 1 when three media were identified: dense phase, dilute phase, and dirty gas. Although incomplete, and upon close study somewhat ambiguous, these descriptors serve as an initial basis for separating the media. The present study will address the dilute phase or the solid in liquid two-phase flow. A preliminary worst-case analysis will be presented along with recommendations for the full consideration of all alternatives by this analysis technique.

2.0 FEASIBILITY MEASURE: THE SONAR EQUATION

As mentioned in the introduction, the simplest form of the sonar equation is,

$$\text{Received signal level} = \text{noise background level.}$$

For our purposes, the one-way transmission equation is used as pictured in Fig. 1, and,

$$SL - TL + PG + DG = NL \quad (1)$$

where

SL = Source level (Pressure) at 1 meter from the acoustic source, (db re μ Pa).

TL = Transmission loss along the path between source and receiving transducer, (db).

PG = Processing gain. The increase in signal relative to the noise due to processing, (db).

DG = Directional gain of the receiver transducer against the background noise, (db).

NL = Background noise level at the receiving transducer, (db re μ Pa).

The normal procedure is to write Eq. (1) on a spectral level basis in which case the pressure intensities are referred to a one Hertz bandwidth. Unless otherwise stated, one Hertz will be the understood bandwidth of the quantities involved. The left side of Eq. (1), the sonar equation, might be termed the "Processed Signal Level" at a receiver input, PSL. It is the received signal level increased by a factor that accounts for the gain in the signal to noise ratio due to signal processing. By writing the noise background level alone on one side of the equation, the basis for the graphic method of showing feasibility, used later in this report, is formed.

3.0 FEASIBILITY ANALYSIS

A medium will be selected and its properties will be stated. Based on the properties of the medium, parameters such as the attenuation constant, the transmission loss, the directional gain, the source level, and the processing gain will be determined. Also based on these parameters, the theoretical low and high frequency limits will be established for the medium under consideration. This frequency range will be used for flowmeter applications.

3.1 The Medium: The Worst-Case

The medium selected is a two-phase liquid/solid non-reacting uniform

- SL, Source level at the inner wall
- TL, Transmission loss through the fluid
- DG, Receiving transducer directional gain
- NL, Background noise level
- PG, Processing gain
- PSL, Processed signal level
- DS, Averaged measurement parameter (Δf , $\Delta \phi$, Δt , etc)
- SLD, Square law detector
- *, Summation

Fig. 1 An elementary sonic transmission flow velocity measurement scheme.

mixture. The worst-case implies only that the characteristics of the medium effecting the transmission have values that result in the highest attenuation of sound. To obtain this, we characterize the medium by

- (1) Particle size
- (2) Concentration
- (3) Density ratio (Fluid/solid)
- (4) Constituents (silica sand/water)

It is necessary for a full evaluation of feasibility to characterize the medium by the following parameters.

- (1) Composition of constituents
- (2) Concentration
- (3) Density
- (4) Sound velocity
- (5) Viscosity
- (6) Compressibility
- (7) Particle size distribution
- (8) Homogeneity
- (9) Isotropy
- (10) Thermal conductivity
- (11) Reactivity (chemical)

These parameters must be known as a function of temperature, pressure, and frequency. It is known that coal, as an example, goes through a complex change of consistency as the temperature is increased and thus would require careful study with regard to the above parameters. No definitive study to determine the acoustic properties of the media in coal conversion processes exists. Thus, comparisons between the actual media and the medium used in this study are necessarily incomplete. Enough information can be obtained from reference 1 and other sources, however, to permit the analysis to proceed. These values are

Medium: Dense phase, fluid/solid (a slurry)

Concentration: 10% by volume

Particle size: 100 microns

Constituents: Solid, rigid particles (sand) in fresh water

The concentration is less than that given for this medium in reference 1 (30%), but this is seen to be the worst case. The particle size is also smaller than that given in reference 1 (5000 microns). Other sources indicate that slurries of coal have a particle size distribution such that 70% will pass through a 200 mesh (70 micron) screen.

3.2 Attenuation Constant

The equation that describes the attenuation constant for rigid incompressible particles that are free to move in a sound field was derived by Lamb and reproduced in reference 3 by Urlick. The regions indicated on Fig. 2 delimit the terms of the attenuation constant equation. The attenuation equation as derived in reference 3 is given by,

$$\alpha = \frac{C}{2} \frac{k^4 a^3}{3} + k (\sigma - 1)^2 \frac{s}{s^2 + (\sigma + \tau)^2} \quad (2)$$

The quantities s , τ and σ for simplification purposes were defined as,

$$s \equiv \frac{9}{4\beta a} \left(1 + \frac{1}{\beta a} \right)$$

$$\tau \equiv \frac{1}{2} + \frac{9}{4\beta a}$$

$$\sigma \equiv \rho_1 / \rho_0$$

where β is the shear wave number in the fluid given by,

$$\beta = \left(\omega / 2\nu \right)^{1/2}$$

and

C = particle concentration by volume

k = wave constant of the fluid

a = radius of particle

ρ_1 = density of particle

ρ_0 = density of fluid

ω = radial frequency

ν = kinematic viscosity of the fluid

Notes:

1. Scattering loss values in the diffraction region are approximate.
2. All data shown is extrapolated from Fig. 1 of reference 3. (Urlick, 1948)

Fig. 2 Viscous and scattering loss for various particle sizes and a volume concentration of 10%, $\rho/\rho_0 = 2.65$

The first of these terms is the scattering loss within the "Rayleigh Region" where the loss is proportional to the fourth power of frequency. The second of these terms is the viscous drag loss and results in the two curves so labeled at 5 MHz and 1 MHz. The data in the "diffraction region" are only approximate and illustrate the general behavior to expect when the particle circumference is of the same order or larger than the sonic wavelength. Exact values for this region would only result from an analysis of the multiple scattering of ultrasound through the two-phase media.

The indications are, that for particle sizes between 10 to 100 microns, the two terms are of similar order and thus the scattering loss cannot be overlooked. To account for both terms, the measured values of the attenuation constants from reference 5 will be used.

The 10% concentration is considered to be the worst case, since this is the value for maximum attenuation. The reason is illustrated in Fig. 3, which is patterned after Fig. 5 in reference 3. This figure shows the dependence of attenuation on the volume concentration of solid particles in water at room temperature. The actual data is for Kaolin particles of density $\rho_1/\rho_0 = 2.65$ and a particle size of about 1 micron. The plot is divided into two regions roughly at 10% concentration. The lower concentration termed the "Proportional Region" and the higher the "Interaction Region." In the proportional region, the viscous loss is additive and proportional to concentration. Above 10%, however, the particles come close enough together so that they interact for reasons that are not clear at present but may be related to the shear coupling across the space between particles or other coupling forces. The result is that the particles motion is "hindered" with a resulting increase in the local viscosity. Using the expression for viscous loss, it may be shown that an increase in the viscosity "with no other changes" actually decreases the attenuation constant. Thus, the maximum value in Fig. 3 represents a worst-case for the attenuation constant. No consideration of thermal conductivity is given here. The fluid is heated by the passage of the wave pressure to a different extent than is the solid, in general, so that heat flows between the two media. The heat flow generates a loss in addition to that caused by viscous drag or scattering. The amount of attenuation due to thermal conduction increases with particle size, but also has a maximum value. This source of attenuation has been ignored, but it is noted that the thermal properties of the suspension must be considered in

Fig. 3 The dependence of attenuation on volume concentration for moderate concentrations. After (Urlick, 1948)

the total assessment of sound absorption. In liquid/solid suspensions the "viscous" attenuation is far greater than the "thermal" attenuation.

3.3 Transmission Loss

The interaction region shown in Fig. 3 requires a more rigorous treatment than has been presented here. The maximum value shown in Fig. 3 for the attenuation constant, α , represents the worst-case. Thus, for a 10% concentration, which is very close to the worst-case, α is equal 1.8. This value of α is large when compared to that of acetic acid, where α is equal to 0.9 at 1 MHz, and to that of water at room temperature, where α is 1200 times smaller than 1.8.

Given the value of 1.8 for the attenuation constant, the transmission loss is related by,

$$TL' = 8.68 \alpha R \quad (3)$$

where,

R = range in cm

TL = TL'/R in db/cm

and thus,

$$TL = 15.6 \text{ db/cm at } 1 \text{ MHz} . \quad (4)$$

It is known that the frequency dependence of the absorption coefficient is as follows,

$$\alpha (f) = \frac{\alpha (f_o)}{f^2} \quad (5)$$

where, f is in MHz and represents the frequency of interest and f_o the reference frequency, which in this case is equal to 1 MHz. It follows that the transmission loss will also have a frequency dependence and is given by,

$$TL = \frac{15.6}{f^2} . \quad (6)$$

A table of TL values is given below for 10% concentration by volume, one micron diameter of Kaolin suspension in water at room temperature and pressure.

<u>f</u> (MHz)	<u>Attenuation</u> (db/cm)	<u>TL</u> <u>1 Meter</u>
0.1	0.156	15.6
0.3	1.404	140.4
0.5	3.9	390
0.8	9.98	998
1.0	15.6	1560

3.4 Directional Gain

Transducers at ultrasonic frequencies exhibit directivity depending upon the active area and the frequency. For a circular transducer, the gain is determined by the diameter to wavelength ratio as,

$$DG = 20 \log \frac{\pi D}{\lambda} \quad (7)$$

For simplicity, we will take a constant directional gain of 24 db corresponding to a D/λ of 5.

3.5 Source Level

For an ultrasonic transducer a source level on the beam of 200 db re μPa at 1 meter is common. The limitation on radiated power is the cavitation threshold which is expressed as the maximum power per unit area. Fig. 4 from reference 4 indicates a cavitation threshold at 100 kHz of 30 watts/cm². The active area of a transducer with $D/\lambda = 5$, $\lambda = c/f$ and $c = 1.5 \times 10^5 \text{ cm/sec}$ (sound velocity of water) at 100 kHz is,

$$A = \frac{\pi D^2}{4} = 44.1 \text{ cm}^2 \quad (8)$$

The total power is,

$$P = 1323 \text{ watts} \quad (9)$$

The source level then becomes,

$$SL = 171.6 + 10 \log P \text{ db re } \mu\text{Pa} \quad (10)$$

The value of 171.6 db re μPa corresponds to a pressure level given up by a source of 1 watt at a distance of 1 meter from the source in water. Using the value for P from Eq. (9) in Eq. (10), the result is,

Fig. 4 Frequency dependence of the cavitation threshold for a CW signal at atmospheric pressure.

$$SL = 203 \text{ db re } \mu\text{Pa at 1 meter at 100 kHz} \quad (11)$$

To allow for loss in efficiency, we take a source level of,

$$SL = 190 \text{ db re } \mu\text{Pa at 1 meter at 100 kHz},$$

which corresponds to

$$SL = 230 \text{ db re } \mu\text{Pa at 1 cm at 100 kHz}.$$

Since the cavitation threshold is increasing with frequency at a higher rate than the area is decreasing (at constant D/λ), this source level value is conservative, especially since the threshold also increases with pressure. There is some lowering of the threshold when pulsed sound is used rather than continuous wave, but the effects are minor.

3.6 Processing Gain

For the processing gain, we take a nominal value of 5 db. The actual value depends upon pulse length, receiving bandwidth, and detection index determined by the probability of detection and false alarm.

3.7 Worst-Case Performance

The worst-case parameters are summarized below.

<u>Parameter</u>	<u>Value</u>
SL	230 db
DB	10 db
PG	5 db
TL	depends upon frequency and range
NL	depends upon frequency and flow velocity

The left hand side of Eq. (1) represents the "Processed Signal Level" at the output of the receiver, that is,

$$PSL = SL - TL + DG + PG, \quad (12)$$

upon substituting the worst-case parameters with the proper values of TL in Eq. (12) the curves for PSL of Fig. 5 are obtained. Recalling that operation of this transmission type of flowmeter is feasible if the PSL value equals the noise background, these curves then show the frequency range for feasibility with the stated conditions, and for a spread of ranges between 1 cm and 1 meter.

Fig. 5 Flowmeter feasibility for a fluid/solid flow medium, 10% volume concentration. Flow Noise Data from Ref. 5, 1/2" Dia. Transducer.

The noise background, which limits the operational range and frequency, is perhaps the parameter with the greatest uncertainty. No direct measurements of NL in coal conversion processes are known to have been made. Two mechanisms of noise production are shown in Fig. 5, namely flow noise and thermal noise. The flow noise shown is for flow velocities of 6 meters/sec. and 15 meters/sec. and is taken from reference 5. This noise represents measured wall flow noise background in a circulating water tunnel, using a 1/2" diameter hydrophone.

The levels have been decreased by 10 db to account for the directional gain of the receiving transducer. Flow noise levels are affected by the presence of solid particles, but the exact consequences are not as yet understood. The wall and pipe flow spectra are also likely to show differences due to the normal modes within the pipe and the flow-induced vibro-acoustics of the pipe wall. Nevertheless, as a first estimate of the noise background, this data serves well.

It is observed that the thermal noise limits operation at frequencies above 600 kHz. Otherwise, the flow noise background is the limiting mechanism.

3.8 Minimum Frequency Considerations

The foregoing analysis has determined the maximum frequency for operation with at least one type of medium. It is useful to inquire as to whether there is a minimum operational frequency according to some criterion. Of course, the full discussion of bandwidth required for operations would depend upon the principle or type of sonic flowmeter considered. It is not the intention of this report to consider all the various types of flowmeters but to illustrate the application of the general feasibility analysis scheme to a simple transmission flowmeter.

For the transmission type flowmeter and measuring phase as a method of determining the flow velocity, we might use the formula,

$$D\phi = \omega DT \quad (13)$$

where,

DT = Minimum time difference to be resolved in the velocity measurement.

$D\phi$ = Minimum phase difference to be resolved in the velocity measurement.

ω = The radial frequency.

This formula ignores the complications of doppler frequency shift, pulse width and detection particulars and can only be considered as a first estimate of the relationship between phase and time-of-flight differences.

For a total path length, R , the time-of-flight is $T + R/c$. If the minimum resolution is expressed as a fraction of the total time-of-flight,

$$A = \frac{DT}{T}, \quad (14)$$

then,

$$DT = AT = \frac{AR}{c} \quad (15)$$

and,

$$D\phi = \frac{\omega AR}{c} \quad (16)$$

Then,

$$\omega = \frac{c D\phi}{AR}, \quad (17)$$

or in terms of frequency,

$$f = \frac{c D\phi}{2 \pi AR} \quad (18)$$

This expression indicates that the minimum frequency of operation depends directly upon the phase resolution and inversely upon the velocity resolution desired and the range.

Suppose a transmission type flowmeter with a path length of $R = D/\cos \theta$ is considered and D is the pipe diameter, then,

$$f = \frac{c D\phi \cos \theta}{2 \pi AD} \quad (19)$$

To be definite, the values

$$D = 1 \text{ meter}$$

$$A = .01$$

$$\theta = 30^\circ$$

$$c = 1.5 \times 10^3 \text{ meters/sec.}$$

$$D\phi = \pi/2$$

are used.

The value for $D\phi$ is hardly a severe restriction upon the phase measurement resolution, then the minimum frequency is,

$$f = \frac{(1.5 \times 10^3) (.866)}{4 (.01)} = 32.5 \text{ kHz} \quad (20)$$

for

$$D = 10 \text{ cm}$$

$$f = 325 \text{ kHz.}$$

These two values are plotted on Fig. 6 along with the values from Fig. 5. Together, the two curves of Fig. 6 indicate the frequency range over which operation of this type of flowmeter is feasible.

4.0 SUMMARY OF RESULTS AND REMARKS

The foregoing analysis shows the feasibility limits for a transmission type sonic flowmeter in a fluid/solid non-reacting medium. From the analysis, the following points may be made:

- (1) Sonic flowmeters are technically feasible for two-phase flow of moderate solids concentration (30% by volume or less) at frequencies below 1 MHz for a 10 cm path length and below 400 kHz for a one meter path length. The calculations are based on the data of Fig. 3 where the attenuation with respect to volume concentration is plotted. For concentrations higher than 10%, the scattering term of the attenuation will affect the results. From the limited experimental data available and noting from Fig. 8 that the attenuation constant is decreasing with concentration, it is believed that the present results can be extended up to a concentration of 30%. A study is underway at the present time that is examining the feasibility of acoustic flowmeters for heavy concentrations of up to 75%.
- (2) The worst-case analysis presented here applies only to the medium analyzed and cannot be considered a general or worst-case condition for all types of flow found in coal conversion

Fig. 6. Flowmeter feasibility lower limits.

and combustion processes. Such an analysis must await the more thorough and detailed characterization of the media associated with any segment of the processes.

- (3) The analysis technique is general, however, and all types of flowmeters may be analyzed within the framework presented here. Thus, a common basis for comparison of technical feasibility is established.
- (4) The preliminary feasibility analysis has not considered the following effects in detail, although some arguments are presented to show the relative contributions of these aspects:
 1. Temperature
 2. Pressure
 3. Particle size distribution
 4. Scattering
 5. Thermal loss
 6. Reacting particles
 7. Entrained fluids or gases
 8. Particle-fluid velocity differences
- (5) The emphasis in this study has been on the flow velocity measurement. However, the quantity of interest is the mass flow rate of solids and gases, usually through a known cross-sectional area. Thus, as is pointed out in reference 1, both the flow velocity and the mass concentration must be known. Acoustic means of measuring both exist, but their feasibility is not treated here. These techniques include the doppler sum and difference where, the sound velocity (related to concentration), and the flow velocity are measured simultaneously.

5.0 RECOMMENDATIONS

Specific recommendations for further assessment of the feasibility of sonic measurement on control devices for the coal industry include:

- (1) Characterize the media in the coal conversion and combustion processes through a program of analysis and experimentation including in-situ sampling and monitoring within the pilot-plants.

(2) Obtain background acoustic noise levels under operating conditions within the pilot and demonstration plants.

(3) Complete the feasibility analysis by consideration of all types of sonic techniques including

1. Transmission
2. Doppler echo
3. Transmission line
4. Passive listening
5. Correlation

within the analysis scheme presented in this report.

(4) Enlarge the scope of feasibility analysis to include cost and scheduling considerations consistent with the requirements for demonstration coal processing plants.

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