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THE DEVELOPMENT OF AN ACOUSTICAL THERMOMETER
FOR A GRAPHITE MATRIX NUCLEAR FUEL ELEMENT

by

J. B. Roes and D. L. Peat

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IN NUCLEAR SCIENCE ABSTRACTS

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THE DEVELOPMENT OF AN ACOUSTICAL THERMOMETER FOR A GRAPHITE MATRIX NUCLEAR FUEL ELEMENT*

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Summary

The development of an acoustical thermometer for use in graphite matrix nuclear fuel elements is described. Test results indicate that this thermometer accomplished the objective of automatically accurately and reliably recording temperatures of a number of sensors. The acoustical thermometer system offers a wider choice of signal transmission line and sensor materials than conventional thermometer systems since it does not require the use of electrical insulators or the conductors in them. This advantage was the main reason for choosing the acoustical thermometer for use in the particular environment of interest.

While the development of the thermometer was directly aimed at the solution of problems associated with a nuclear and carbonaceous environment, a number of observations are presented that should be pertinent to acoustical thermometer design in general.

Introduction

The development of high temperature graphite moderated nuclear reactors at General Atomic created the requirement for measuring fuel temperatures up to 1500°C in a carbonaceous nuclear environment for periods up to ten years. State-of-the-art thermocouples have proved incapable of meeting this need. In 1961 Dr P H Miller of General Atomic suggested the use of an acoustical thermometer† that was subsequently successfully developed, tested, and used for the Peach Bottom nuclear power plant.^{1,2} While this device accomplished the original objectives, it demands manual adjustment of the acoustical source and visual interpretation of an oscillogram displaying echo signals. Larger nuclear stations contemplated later required as many as 60 in-core temperature measurements, manual operation therefore became impractical and a requirement for automatic recording thermometers was

established. Subsequently the program described herein was undertaken to investigate various acoustical thermometer systems culminating in the development of a device with the desired characteristics.

Basic Acoustical Thermometer System

It can be shown (see the Appendix) that the velocity of sound in a monatomic gas is $V = \sqrt{\gamma RT/M}$, where γ is the ratio of specific heats, R is the specific gas constant, T is the temperature (in degrees Kelvin) and M is the atomic mass. The measurement of the velocity of sound can be conveniently accomplished by means of electroacoustical transducers. However, the transducers should be remote from the measurement area if the acoustical thermometer is indeed to offer advantages over an electrical measurement. A typical acoustical thermometer (Fig. 1) will thus consist of the following components:

- 1 Velocity of sound sensor
- 2 Acoustical transmission line
- 3 Electroacoustical transducer
- 4 Electronic circuit and readout system

Development

System Requirements

The development of the acoustical thermometer was guided by the following requirements set by General Atomic's HTGR reactor design group:

Temperature range	20° to 1500°C
Minimum accuracy and repeatability	±3% of °K
Minimum life	3 yr
Environment	Helium graphite nuclear reactor core
Distance from electroacoustical transducer to fuel rod standoff pin	50 ft
Distance from standoff pin to sensor	8 ft
Length of sensor	5 ft max
Volume of sensor	5 in ³ max
Number of sensors	60
Reporting mode	Automatic 10 min cycle

*Work supported by U S Atomic Energy Commission Contract AT(04-3)-167 Project Agreement No. 17

†U S Patent pending General Atomic Division General Dynamics Corporation San Diego California

Various Approaches

The simplest solution to the materials problem posed by the above requirements is obviously the use of graphite acoustical components in the graphite matrix nuclear fuel elements. In addition to the components shown in Fig 1, any system for measuring fuel element temperatures must incorporate a standoff pin that provides a transition from a metal transmission line to the graphite line in the fuel element and permits the element to be removed without difficulty. The standoff pin is thus a rather loose joint. In practice it has proved far simpler to construct a standoff pin with a known leak than one with a hermetically sealed tube transition.

In Ref 1, a temperature measuring system is discussed which uses a resonant cavity in the fuel element, coupled by a single tube to a remote transducer. An electronic package provides a short burst of monochromatic sound. The frequency of this sound is manually adjusted until a characteristic echo is observed on an oscilloscope showing that the excitation frequency corresponds to the resonant frequency of the cavity. The size of the cavity being known, the frequency can be translated to velocity of sound and temperature. This method has proved to be quite practical for installations where a small number of sensors are required. The graphite part of this system must be made of HLM 85, a particularly dense material, to limit transmission losses and maintain a reasonable quality "Q" in the cavity. Tests showed that the accuracy of this system at constant pressure was not less than $\pm 1\%$ of $^{\circ}\text{K}$ and the pressure dependency was less than 2% of $^{\circ}\text{K}$ between 100 and 350 psi.

An all-metal system has also been made, which operated in an automatic mode. This system used two transmission lines, one exciting the cavity and the other listening for resonance. By frequency modulating the sound source, a servo system that coupled the received signal to the sound source continually adjusted for the cavity resonance frequency. While a metal acoustical system of this type works well with a metal cavity one being in actual use at Los Alamos Scientific Laboratory, a number of complications arise with a graphite acoustical system. Under the program described here these problems were found to be

- 1 Fabrication of 8 ft sections of graphite double tubing without cracks or leaks was difficult to accomplish.
- 2 The standoff pin for this system was to have no leaks between the two acoustical transmission lines.
- 3 The combination of transducer response and standing waves in the transmission line system produced peaks in the response of the system that were indistin-

guishable from the relatively small signals from the graphite resonant cavity. The servo system would thus lock onto a peak other than cavity resonance.

At this point in the program P. H. Miller Jr., who had built a simulator for imitating seismic reflections in earth's strata by the use of a set of pipes of different diameters in 1961 suggested using such diameter changes to produce echoes. He noted that each variation in diameter caused an acoustic impedance discontinuity and the time between reflections depended on the length of the pipe and the molecular weight and temperature of the gas, and therefore could be used for accurate temperature determination in a nuclear reactor environment (Fig 2). In terms of previous tests, this method uses a strongly coupled cavity of low Q. Sound is introduced in the form of a pulse. The first change in diameter produces one echo and the end of the sensing section a second echo. The time interval between echoes is translated into velocity of sound and temperature. Since only one set of echoes is involved, there is no use of resonance and any single pulse containing only frequencies above the cavity resonance can be employed to excite the system. Such a system is of a broad-band type and can acquire any temperature within its range without adjustment. This in turn permits one electronic system to serve a large number of thermometers by means of switching.

System Design

Velocity of Sound Sensing Section Economic considerations made it very desirable to use ACOR reactor grade graphite rather than HLM 85 graphite. This required that the lowest possible frequency be employed to limit attenuation due to porosity.

In determining the time interval between two pulses with a given frequency content higher accuracy is obtained if the interval is longer. The section for sensing the velocity of sound was therefore chosen to be the longest permissible length (5 ft).

At 1500°C the velocity of sound according to Eq (9),* is approximately 2500 ft/sec. The first echo occurs at the entrance of the transmission line to the sensing section. The second echo occurs after the remaining sound is bounced off the end of the sensing section. The second echo thus travels $2 \times \ell$ cavity further than the first, or $2 \times 5 = 10$ ft. The time interval between the two echoes at 1500°C is therefore

$$\frac{2\ell}{V} \approx \frac{10}{2500} \text{ sec} \approx 4 \times 10^{-4} \text{ sec}$$

In order to obtain two independent echoes each should be no longer than 400 microsec. The signal

All numbered equations appear in the Appendix

can have a rise and fall time of 200 microsec the frequency content of such a signal being mainly at 2 kHz and at the repetition rate. The latter can be made so low that each measurement is done with only one excitation pulse in the acoustical system.

For a given frequency, the acoustical transmission line will be more efficient if its diameter is made larger. The largest diameter that could be accommodated without undue cost or complication, 1/4 in. ID, was therefore chosen. The sensing section is of smaller diameter than the transmission line so the echo from the first transition equals the echo of the remainder of the pulse after it travels twice the length of the sensor and re-enters the transmission line. Application of Eqs. (13) and (15) shows that for a given diameter change the ratio of the two echo amplitudes is density dependent and thus changes with temperature. However, it was shown experimentally that this ratio does not change more than 1.3 over the pressure range 50 to 450 psi and the temperature range 20° to 1500°C. A convenient median value of 3/16 in. ID was therefore selected.

The main reason for using a sensing section of smaller diameter than the transmission line is that the echo from the diameter transition point is of the same sign as the one from the closed end of the sensing section. This somewhat simplifies the electronic circuit for temperature readout. A smaller diameter would normally attenuate sound at a higher rate (Eq. (13)). However, the temperature of the sensing section is usually much higher than the temperature of the transmission line, which reduces density in the sensing section and makes the attenuation per foot substantially the same in both tubes. For example, according to Eq. (13), attenuation, α , at 2 kHz in a 1/4 in. ID tube with 450 psi helium is 0.42 db ft⁻¹ at 100°C. A 3/16 in. tube under identical conditions would have an α of 0.60 db ft⁻¹ while a 3/16 in. tube at 1000°C would have an α of 0.28 db ft⁻¹.

The initial sensing section design consisted of a 5 ft ACOR graphite tube of 3/16 in. ID. Later, attempts were made to increase the sound path in the sensing section by folding the section. This required a 180° bend in the graphite tube. A folded sensing section was made of ACOR graphite, but tests showed that a considerable loss in high frequency content of the pulse occurred at the bend and also that a significant low frequency path existed through the porous graphite between the two parallel tubes. This approach was therefore abandoned. It is noted, as a matter of interest, that a metal folded sensor using an elbow with a 3/4 in. radius

operated very well without noticeable effects being induced by the bend. A spiraled metal tube with a 2 in. winding radius also operated satisfactorily.

Another attempt was made with a more loosely coupled graphite cavity to use the first and third reflections, increasing the sound path in the sensing section by two by resonance. With this mode of operation, it is impossible to have the third echo equal to the first and second, which results in complications of signal handling. This mode of operation does not significantly extend the temperature range, because it is limited by overlapping of the first, second, and third echoes. At best, a gain in accuracy of two is accomplished at a given temperature. The advantage of a resonant cavity was not considered sufficient to warrant the extra complication.

An interesting side effect was noticed in this test when a larger diameter cavity was connected to a smaller diameter transmission line. If the orifice coupling was located in the center of one end of the cavity, the high frequency part of the first reflection from the closed end of the cavity entered the transmission line and was not available for resonance. Subsequent signals contained only lower frequencies and were of little use. However, if the orifice was offset from the center, frequency content in all reflections could be made more nearly equal. This revealed very clearly the effect of viscous drag and turbulence, as shown in the Appendix (Fig. 5).

Evaluation of miscellaneous effects on the velocity of sound in the sensing section showed the following:

1. Dissociation. This is not a problem with a monatomic gas.

2. Isothermal sound. Application of Eq. (20) yields a V'/V ratio at 1000°C of approximately 0.995. Therefore, the velocity of sound in a smooth 3/16 in. ID tube is reduced by 1/2%. Equation (20) indicates a dependency on density and thus pressure and temperature. Experiments have shown that the effect for porous and rough tubes can be several times the effect for smooth tubes. For example, for a 3/16 in. tube of ACOR reactor grade graphite, the reduction in velocity of sound in the tube is of the order of 1%. Since the roughness and porosity of a tube can be expected to be reasonably constant over a long period, their effect on acoustical temperature measurement can be corrected for by calibration.

However, the measurement has now become somewhat density dependent

3 Ratio of sound particle velocity, V_s , to thermal particle velocity, V . The displacement of the gas at the sound source, with the transducer used, cannot exceed 0.3 mm. The particle velocity is thus $2\pi f \times 3 \times 10^{-2} \text{ cm/sec}^{-1} = 3.78 \times 10^2 \text{ cm/sec}^{-1} \text{ max}$. Before this sound reaches the sensing section it is attenuated by at least 50 ft of transmission line at a rate of approximately 0.4 db/ft $\approx 20 \text{ db}$. The displacement in the sensing section is thus $3.78 \times 10 \text{ cm/sec}^{-1}$. At room temperature the mean particle velocity of the helium is approximately 10^5 cm/sec^{-1} . The relation between V_s and V is thus 3.78×10^{-4} , which for present purposes is negligible. At higher temperatures the effect will be even less.

4. Ratio of molecular volume to gas volume and van der Waals forces. From Ref. 3 we find the van der Waals constants for helium

$$a = 3.412 \times 10^{-2} \text{ liters}^2 \text{ atm},$$
$$b = 2.37 \times 10^{-2} \text{ liters/mole}.$$

For a typical operating temperature of 1000°C , the real gas equation (11) differs from the perfect gas equation (1) to increase the velocity of sound by 0.45%. This effect is again density dependent.

Of the four effects discussed above, only the second and fourth are of significance in our case. Both of these effects are related to pressure which is a secondary measurement. The two effects tend to compensate for each other, and their combined effect should not exceed a 1% reduction in velocity of sound in a straight 5 ft 3/16 in. ID ACOR graphite section.

Acoustical Transmission Line. As stated previously, 1/4 in. ID was chosen as the maximum diameter for the transmission line that would not be unduly expensive or difficult to install. Equation (13) predicts an attenuation at 2 kHz of 0.42 db/ft⁻¹. This value was experimentally verified and found to be valid for smooth metal tubing. Tubing fabricated from HLM 85 graphite showed less than 10% more attenuation at 2 kHz, while tubing fabricated from ACOR reactor grade graphite produced an attenuation value approximately twice that for metal tubing. These values were found by measuring the effect on amplitude of the echo of a typical pulse in an acoustical system that was changed in length by inserting a 5 ft section of the tubing to be tested. The system contained a 50 ft section of metal

tubing of the same internal diameter as the tubing under test and was closed at one end. The difference in amplitude caused by introduction of the test tube gave the attenuation of twice the length of the test tube from which the attenuation per foot was simply derived.

It was shown experimentally that a tight transition of stainless steel tubing to ACOR reactor grade graphite produced a signal which was at least equal in magnitude to the echoes from the sensing section but was opposite in phase. It was further shown that a loose sliding fit with a 1 in. overlap produced an echo with three times the amplitude of the sensing section echoes.

Electroacoustical Transducer. The transducer was of an electromagnetic type. The impedance at 2 kHz was approximately 100 ohms. The transducer unit was enclosed in a pressure housing. The membrane resonance was close to 2 kHz.

By supplying a 60 volt pulse of 400 microsec duration in such a way that it reinforces the field of the permanent magnet, the membrane is pulled into a position close to the magnet. At the end of the pulse the membrane is released and bounces back in 200 microsec. The relaxing membrane produces the desired pressure pulse. This method makes efficient use of the magnetic circuit, since mechanical energy is accumulated in the membrane and then released at a higher rate than the rate at which it was supplied by the magnetic circuit. While the membrane is being cocked, little acoustical energy is delivered.

It has been determined experimentally that the transducer assembly has harmonic linearity to 60 volts and that the efficiency of electrical to acoustical power transfer is 1% or -20 db per transfer. By using a 400 microsec excitation pulse and membrane energy storage, transfer of -34 db is provided from signal in to signal out.

Using an instantaneous power of 36 watts on this transducer is permissible only at low duty cycles. At 10 pulses per second, the power input is 144 milliwatts, and no significant temperature rise of the transducer has been observed at this rate. The coupling of the transducer to the tube is such that the membrane is strongly damped at its natural frequency. Harmonics and other modes of vibration of the membrane persist for several milliseconds, but since they are at higher frequencies, these are effectively filtered by the transmission line.

The transient response of the transducer was determined from echoes received from a closed end tube with known characteristics. Frequency response was determined for two

transducers, A and B, by connecting transducer A to a third transducer, C, with 10 ft of tubing of known characteristics, then B to C, and then A to B. This provided the transfer functions, Log A + Log C and Log B + Log C, from which Log A - Log B was derived. Taken with Log A + Log B and Log A + Log C, this yielded Log A, Log B, and Log C. The 10 ft tube introduced errors due to standing waves, but as these are repetitive and more frequency dependent than the response of the transducer, they could simply be averaged out.

Signal Strength From the foregoing, the amplitude of the echo signals could be determined

Pulse amplitude	60 Volts
Transducer	-14 db
2 x 50 ft at 0.42 db/ft at 100°C	-42 db
Standoff pin	-1 db
ACOR graphite transmission line at 100°C	-13 db
First echo	-1 db
ACOR 5 ft sensor at 100°C	-10 db
Absorption of end plug of sensing section	-5 db
Transducer	-20 db
	-106 db

This result was sufficiently encouraging that a complete mockup was constructed

At room temperature the amplitude of the returned echoes was approximately 300 microvolts, the expected value. At higher temperatures of the sensing section this value increased to approximately 1 millivolt

Noise The main source of noise proved to be that transmitted through the metal to the transducer. The membrane acts as an inertial mass while the body of the transducer moves; such a system has a response which increases with frequency. Metal is a far better medium for the transmission of sound than gas. Therefore, in a loosely assembled system, resonances and reflections can still be present in the metal system after the arrival of echoes through the gas. In a pulse system this is manifested by high frequency noise at large amplitude long after the main pulse has been produced. This effect can be substantially reduced by anchoring all components onto a rigid system. The remaining high frequency noise can be effectively reduced by a low pass filter to 1 microvolt rms

Tests on sound transfer between tubes included welding two tubes 1 in. apart in a flange, with one tube connected to a variable frequency sound source and the other to a microphone.

When the tubes were firmly held in place, over their entire length, transfer between 2 and 10 kHz was accomplished with at least -100 db attenuation, as expected (see Eq. (17)). When the tubes were not anchored, and were touching each other, transfer at certain frequencies was accomplished with less than -20 db attenuation owing to standing waves generated in the metal

Signal-to-Noise Ratio. Noise generated from extraneous sources can normally be expected in a nuclear power plant. However, the amount of noise has not yet been measured, and it could only be verified that tapping noises and noises generated by motors connected to the acoustical system did not interfere with the measurement. It was demonstrated that the system withstood a reasonable amount of this type of noise, but this problem should be further investigated. Improvements in the signal-to-noise ratio may best be realized by raising the sound level of the sound source

Electronic Circuit (Refer to Fig. 3) The transducer is energized by a pulse generator (Waveform A). The echo signals (B) are amplified by a low noise high gain preamplifier (C). Input overload is limited by a diode limiter to approximately 0.5 volts, which is adequate for recovery prior to the arrival of the desired signal. The amplified signal is filtered by a low pass filter to remove all frequencies above 2 kHz (D). A 10^{-5} sec differentiator accurately locates the zero slope points (peaks) of the filtered waveforms. The derivative is then reamplified by the derivative amplifier (E).

The signal detector is a Schmitt trigger with controlled bias and hysteresis. The trigger is set on the descent of the derivative signal and the hysteresis is adjusted so that the circuit resets as the derivative goes through zero (F).

The signal selector is another Schmitt trigger with controlled bias and hysteresis, which operates near the peak positive value of the undifferentiated signal. Pulses (H) are thereby generated which operate an "and" gate to select only that portion of the detector output corresponding to the positive peaks of the original signal (D).

The large negative standoff pin echo operates a Schmitt trigger (J) which, in turn, operates a one-shot (K) with a time corresponding to the minimum delay in the graphite part of the transmission line. A second one-shot then generates a pulse (L) longer than the maximum delay in the sensing section plus the difference between maximum and minimum delay in the

graphite transmission line. Pulses (L) and (H) thus open the gate to the output flip-flop only when the sensor echoes are due.

The output flip-flop is clamped for some time after the pulse transmission so that spurious signals will be ignored and to assure setting in the proper position. It produces a square pulse (G) whose width is determined by the time between the sensor echoes (F). After double integration, this output is indicated on a 0 to 10 millivolt strip chart recorder as a dc voltage inversely related to the square root of the temperature.

Test

For testing purposes, the graphite section of the acoustical system was mounted in a stainless steel pressure vessel. A strip chart recorder indicated a value proportional to $1/\sqrt{T}$. By means of a square root extractor, it is possible to make the recorded temperature scale linear. However, this introduces an additional error of 1% that can be avoided by not using a root extractor and calibrating the strip chart. The latter method is therefore preferred.

For the test, the sensing section was shortened to 4 ft in order to obtain signals at approximately 800°C that would appear with a 5 ft section at 1500°C. Figure 4 is a plot of temperature, measured with a National Bureau of Standards traceable thermocouple, as a function of $1/\tau^2$, where τ is the time interval between echoes as indicated by the strip chart recorder. To at least 700°C, the plot is a straight line. At 760°C there is a departure from the straight line caused by significant overlapping of the two echoes that distorts the peaks in such a way that their apparent interval is shorter. The departure at this point is 22°C, or just over 2% of °K, and can be corrected for. It was shown that if the system were disconnected from the transducer, it would indicate the correct temperature within 3 sec after reconnection. This indicated that a multi-point recorder driving a switch from sensor to sensor could in effect survey all 60 thermometers in 3 min with one electronic package.

Conclusion

An acoustical thermometer for measuring fuel temperatures in a graphite moderated nuclear reactor core has been developed which fulfills the requirements of accuracy and automatic recording. The acoustical thermometer is of special interest because it is useful over such a large temperature range from cryogenic temperatures to the highest temperature at which solid materials exist. The relation of temperature to velocity of sound in a gas is a primary one and the acoustical

thermometer has, in ordinary configurations, the capability of a primary standard. In unusual circumstances where it is necessary to use an acoustical thermometer, however, secondary effects are often emphasized and the absolute temperature measurement is compromised.

Appendix Discussion of Theory

Relation of Velocity of Sound to Temperature in a Gas

To understand the velocity of sound in a gas as related to temperature, one may begin with the equation of state

$$p v = RT \quad (1)$$

where p is the gas pressure, v is the gas volume, R is the specific gas constant, and T is the temperature in degrees Kelvin.

The virial theorem of Clausius leads to

$$RT = \frac{1}{3} \overline{C^2} \quad (2)$$

where $\overline{C^2}$ is the mean of the squares of molecular velocities. The energy of a molecule consists of translational energy E_t with three equal degrees of freedom. In the case of multiatomic molecules, the internal energy in addition to E_t is distributed in other degrees of freedom such as rotational and vibrational energy.

For a monatomic gas the internal energy per unit mass is

$$E_t = \frac{1}{2} \overline{C^2} \quad (3)$$

Combining Eqs. (2) and (3) yields

$$RT = \frac{2}{3} E_t \quad (4)$$

For a gas with a mass M

$$E_t = \frac{1}{2} M \overline{C^2} \quad (5)$$

Combining Eqs. (4) and (5) yields

$$\overline{C^2} = \frac{3 RT}{M} \quad (6)$$

The mean of the velocity squares of one degree of freedom of a monatomic gas is

$$\overline{C_x^2} = \frac{1}{3} \overline{C^2} \quad (7)$$

Combining Eqs. (6) and (7) gives

$$\overline{C_x^2} = \frac{RT}{M} \quad (8)$$

where $\sqrt{C^2_x}$ is Newton's isothermal value of the velocity of sound. This velocity is approached for example in transmission of sound through small diameter tubes where a large fraction of the heat produced by each compressional wave is conducted to the wall of the tube. In large diameter tubes or large volumes a correction must be made for the local heating and cooling of a gas as a sound wave passes, i.e., for the change in the velocity of sound due to the sound. The ratio of specific heats, γ , is therefore introduced and the velocity, V , of sound becomes Laplace's adiabatic value

$$V = \sqrt{C^2_x \Delta p x}^\gamma = \sqrt{\frac{\gamma RT}{M}} \quad (9)$$

It can be shown that

$$\gamma = 1 + \frac{2}{r} \quad (10)$$

where r is the number of degrees of freedom

Monatomic gases	$r = 3,$	$\gamma = 1.66,$
Diatomic gases	$r = 5,$	$\gamma = 1.40$
Triatomic gases	$r = 7,$	$\gamma = 1.29$

Difficulties arise with polyatomic gases when they are in a state of partial dissociation, which occurs quite readily at high temperatures. This difficulty does not, of course, exist with monatomic gases.

Equation (9) is sufficient for describing the relation between the velocity of sound and temperature to a degree that permits temperature measurement by velocity of sound measurement to, in most cases, 1% of T . Equation (9) shows that there is a linear relationship between the square of the velocity of sound and temperature, which for a given gas is independent of pressure. A number of factors cause discrepancies in the velocity of sound

- 1 Dissociation effect on M and γ ⁴
- 2 Degree of isothermal sound
- 3 Relation between sound particle velocity, V_s , and thermal particle velocity, V . Equation (8) assumes that $V_s \ll V$
- 4 Ratio of molecular volume to gas volume and effect of van der Waals forces

The effect of these factors on the particular measurement method used should be evaluated

van der Waals has made a correction for the fact that gas molecules cannot be considered point masses but have a finite volume that is not

available for compression. He has further corrected for the intermolecular forces which tend to reduce the pressure of the gas.

The equation of state for a perfect gas is thus modified to the following equation of state for a real gas

$$pV = RT \left(\frac{1}{1 - b + \frac{1}{d}} - \frac{aP}{RT} \right) \quad (11)$$

$$\text{where } \frac{a}{b} = \frac{27}{8} RT_{\text{critical}} \quad ,$$

$$\frac{a}{b^2} = 27 P_{\text{critical}}$$

a and b have been determined experimentally for various gases. ³

If a gas is near critical conditions, the velocity of sound is better described in relation to the adiabatic bulk modulus and the density, since they become the dominant variables under these conditions. ⁵ For our particular development we will not approach critical gas conditions, and the equation of state accurately describes the gas.

Acoustical Transmission Line ^{6, 7}

The acoustical transmission lines considered are those consisting of gas filled round tubes. The requirement on the tube material is that the product of density and velocity of sound in the wall material differ greatly from the product of density and velocity of sound in the gas. All solid materials known exhibit this property. We will first consider the propagation of sound in smooth tubes. Attenuation of sound in smooth tubes is due primarily to heat conduction and viscous drag. Figure 5 shows a tube in which a plane sound wave propagates under the influence of these loss mechanisms.

Attenuation of sound in tubes is described by the following equation ⁸

$$A = A_0 e^{-\alpha x} \quad (12)$$

where A is amplitude (pressure or volume current) at a distance of x centimeters from amplitude A_0 , and

$$\text{exponent } \alpha = \frac{1 + 1.58(\gamma^{1/2} - \gamma^{-1/2})}{r V} \sqrt{\frac{\pi f \mu}{d}} \quad (13)$$

where r = radius of the tube,
 f = frequency,

μ = viscosity coefficient 8.76×10^{-5} poises
for helium at 20°C ,⁹

d = density of the gas

We note that in Eq (13) $1 + 1.58 (\gamma^{1/2} - \gamma^{-1/2})$ describes the ΔT due to the sound r describes the heat path and V describes thermal conductivity. The first term thus describes losses due to heat conduction.

In the second term f is proportional to displacement per unit time and d is proportional to specific mass, pressure, and temperature. Together with μ , these describe the attenuation due to viscous drag. For a given gas, pressure, and temperature attenuation is

$$\alpha = C \frac{\sqrt{f}}{r}, \quad (14)$$

indicating that (as expected) less attenuation occurs with lower frequency and larger diameter. Experiments performed at General Atomic with stainless steel and copper tubes of 3/16 in. and 1/4 in. ID and using helium at between 50 and 450 psi and sound between 100 Hz and 10 kHz have validated the above formulae (Eqs. (12) and (13)).

It would now be relatively simple to construct an acoustical transmission line of smooth metal tubing with predictable characteristics. Unfortunately, in many cases, the use of an acoustical thermometer is justified only when no metals can be used in or near the measuring area. The use of metal oxides or graphite is then indicated, which have associated with them rough surfaces, porosity, diameter changes, and leaks. The effects that these factors have on sound conduction are considered briefly below. It is assumed that the individual disturbances are small in relation to the wavelength of sound.

Surface roughness results in increased turbulence of the sound wave closest to the tube wall. This causes the directional velocity to become thermal and the sound to be attenuated.

Porosity affects the conduction of sound in several ways. First, a certain amount of sound is lost by transmission through the porous wall. This amount is inversely proportional to frequency. Second, the sound reflected from the walls is not reflected from the gas-solid boundary, but from an area more or less deep into the porous solid. The gas-solid interface is ill-defined, and where the sound passes through the porous solid, the velocity is the isothermal value which is less than the velocity in the tube. In addition to the heat loss of the sound to the solid, the wavefronts close to the wall are substantially

retarded. This effect is proportional to frequency. Third, porosity often exists in the form of small cavities connected by smaller tubes. Such a system is a multicell integrator capable of releasing energy at a very slow rate compared with the step function of a wavefront. While the former is small in amplitude in relation to the latter, the overall characteristic of the system for preferring the lower frequencies often makes this effect noticeable. Integration is proportional to frequency.

We consider next the effect of abrupt changes in diameter of an acoustical transmission line. If S_1 is the cross section of the sound path in tube 1 and S_2 the cross section of the sound path in tube 2, and the sound travels from tube 1 to tube 2, the reflected pressure or volume current, I' , in terms of the incident pressure or volume current, I , is

$$I' = \left(\frac{S_1 - S_2}{S_1 + S_2} \right) I \quad (\text{taken from Ref. 8}) \quad (15)$$

It can be seen from Eq (15) that if $S_1 < S_2$ the reflected signals are in phase with the incident signals, and if $S_1 > S_2$ the reflected signals are in opposite phase with the incident signals. The ratio of the transmitted power, $P - P_2$, to the incident power, P , is

$$\frac{P - P_2}{P} = \frac{4r_{A1} r_{A2}}{(r_{A1} + r_{A2})^2} \quad (\text{taken from Ref. 8}), \quad (16)$$

where

$$r_{A1} = \frac{dV}{S_1} \quad \text{and} \quad r_{A2} = \frac{dV}{S_2}$$

with d being density and V being velocity of sound.

Expressed in terms of acoustical resistance, the above formula (16) becomes of more general use since it gives the transfer function of sound from any medium to another. In the case of two consecutive changes in acoustical resistance, the ratio of transmitted power to medium 3 in terms of incident power in medium 1 is

$$\frac{P_3}{P_1} = \frac{4 \frac{r_{A1}}{r_{A3}}}{\left(\frac{r_{A1}}{r_{A3}} + 1 \right)^2 \cos^2 kl + \left(\frac{r_{A1}}{r_{A2}} + \frac{r_{A2}}{r_{A3}} \right)^2 \sin^2 kl} \quad (\text{taken from Ref. 8}), \quad (17)$$

where l is the length of sound path in medium 2
 $k = 2\pi/\lambda$, and λ is the wavelength in medium 2 =
 V/f

Leaks in the acoustical transmission line are assumed to be discrete openings more than one wavelength removed from each other. Leaks can then be treated as abrupt increases in tube diameter, consisting of S tube + S leak, with respect to the power P_r reflected by them. Actual power loss due to the leak can be estimated by using Eq (16) or Eq (17), as appropriate, to determine the power, P_L , carried away by the leak. The transmitted power, P_t , in terms of incident power, P , is then

$$P_t = P - (P_L + P_r) \quad (18)$$

Admittedly, this is a coarse method. In practice however, many types of leaks occur that are more easily evaluated experimentally than theoretically.

Acoustical Velocity of Sound Sensor

While reflection and attenuation are of prime interest in a discussion of sound transmission, a discussion of the velocity of sound sensor should be concerned primarily with the effects relating to the accuracy of this measurement.

A suitable velocity of sound sensor will usually consist of a tube with accurately known boundaries. The measurement of the velocity of sound in the tube is then accomplished by relating the acoustical transit time, τ , of a known gas in the tube to the tube length, l . The accuracy with which the length of the tube is known is thus directly related to the accuracy of the velocity of sound measurement. The length of a sensor tube can be affected by temperature, recrystallization and nuclear radiation.

The effects of thermal expansion on materials are well known, and a correction factor can be introduced using the materials expansion coefficient, α . The velocity of sound in the tube is then

$$V = \frac{l_o + l_o \alpha t}{\tau} \quad (19)$$

Without this correction, 1% errors can occur.

Recrystallization and nuclear radiation are time dependent variables. The former occurs at high temperature and is closely related to the material used, the latter occurs only in nuclear reactor cores. Both can be measured independently and then corrected for.

In addition to phenomena directly affecting length of the sensor, it is necessary to consider those effects that complicate the determination of sensor length. These are porosity and mode of coupling to the transmission line. As was discussed in relation to transmission lines, porosity causes the acoustical gas-solid interface to lie more or less deeply in the solid, the deepness depending on porosity and on the inverse of frequency. Because of the difficulties encountered in describing porosity, this effect is best determined experimentally.

The coupling of a sensor to a transmission line is generally accomplished by means of an orifice. If the cross section of the orifice is an appreciable fraction of the cross section of the sensor, nonlinearities in fluid flow (turbulence) in and out of the transmission line will tend to make the sensor effectively longer. Again, these small effects are best determined by experiment.

In order to determine to what extent the velocity of sound is influenced by the sensor walls, we will consider how the velocity of sound in an isothermal gas (small tubes) differs by a factor γ from the adiabatic velocity of sound (large tubes). Helmholtz¹⁰ and Kirchhoff¹¹ have calculated the changes in velocity of sound as related to the radius of a smooth tube to be

$$\frac{V'}{V} = 1 - \frac{\sqrt{\frac{2}{5}} \mu/d}{r} \quad (20)$$

where V' is the corrected velocity of sound.

For a given gas the change in velocity of sound is dependent not only on tube radius but also on frequency and pressure. Tubes with a porous or rough wall have a further tendency to bring the velocity of sound in the contained gas to the isothermal value owing to increased thermal contact and turbulence. We will not attempt to describe these factors quantitatively.

In the preceding discussions, the use of a known gas has been assumed. In practice care must be taken by repeated bakeout and evacuation to remove all foreign volatile materials.

Transducer

Transducer theory is discussed in a number of specialized books¹²⁻¹⁴

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Fig. 1--Basic acoustical thermometer

Fig. 2--Double pulse acoustical thermometer, using diameter change in transmission line for sensor boundary marker

Fig. 3--Block diagram of double pulse acoustical thermometer

Fig 4--Calibration curve for acoustical thermometer

Fig 5--Plain soundwave in tube under influence of loss mechanisms