THE RICE INSTITUTE

DESIGN AND CONSTRUCTION OF APPARATUS FOR DETERMINING THE VELOCITY OF SOUND IN GASES AT HIGH PRESSURES AND TEMPERATURES

BY

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P R E F A C E

Originally this work was planned to be devoted to measurements of acoustic velocity in superheated steam. But by the time this thesis was written, no definite measurements on steam could be taken due to several difficulties arising in connection with construction and design of the apparatus. Therefore few data were taken on carbon dioxide at room temperature in order to prove the accuracy of the equipment and its suitability for further work in steam.
The purpose of the present work is to present results obtained from studies using a variable path type interferometer designed for generating sound waves above the audible limit in gases at high pressures and temperatures.

Ultrasonic or high frequency sound waves are generated by means of a quartz crystal vibrating at its fundamental frequency. The crystal is placed on top of a vertical cylinder which is fitted with a moving piston or reflector. In this way a series of standing waves is produced. As the piston is moved in the cylinder, a periodic reaction of voltage occurs across the crystal as the piston moves through successive half wavelength sound intervals. The acoustic velocity or the velocity of sound in the gas is the product of the frequency of the sound source and measured wavelength interval.

An electrical driving oscillator of the "electron coupled" type is used to drive the crystal at its natural frequency. The frequency of the driving oscillator is determined by "beating" against a crystal controlled oscillator of known frequency. Voltage change appearing on the crystal is measured by a vacuum tube voltmeter.

A heating system using superheated steam is used to maintain constant temperature conditions in a steel jacket or tank in which the interferometer is housed.

An automatic photographic recording apparatus is used to obtain a curve representing voltage variation vs piston displacement which is
driven through suitable gearing from the piston rod. Knowing the scale of the ordinate or drum speed, the wave length can be evaluated.
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INTRODUCTION

Science of ultrasonics has its origin in late decades of nineteenth century. One of the earliest investigators of inaudible sounds was probably Despretz who in 1845 set the upper limit of sound waves at about 30,000 cy. per sec.

Galton in 1883 designed a whistle for the production of sounds near and beyond the upper limit of human audibility.

In 1899 Krenig investigated the region above the limit of audibility by means of tuning forks only a few millimeters in length, reaching in this way frequencies as high as 90,000 cy. per sec.

Since that time many investigators broadened the field of ultrasonics. The first ultrasonic measurements by means of an acoustic interferometer were done by Pierce in 1925. He made the first measurements in CO₂ and found that the acoustic velocity is dependent upon frequency.

It would take too much space to list all investigators using vibrating quartz to measure the velocity of sound: Pielmeier, Thompson, Reid, Loomis, Klein, Hershberger, and many others paved the way of knowledge in ultrasonics. At present Hubbard and Herget have compiled extensive data on nitrogen and carbon dioxide and J. Woodburn measured acoustic velocity in superheated steam.

Ultrasonic interferometry is no longer a laboratory curiosity, but a very important tool in investigation of acoustic velocities, and absorption in fluids and solids.
During the past few years industrial firms, particularly the steel industry, have used ultrasonics as a means of detecting flaws in castings and billets as a method of non-destructive testing.
Piezoelectric Effect.

The heart of an acoustic interferometer is a quartz crystal which serves as a generator and a receiver of ultrasonic energy. Most of the crystals possess these properties which we call piezoelectric effect. "Piezo" is derived from a Greek word meaning to press, and piezoelectricity is pressure electricity. Piezoelectricity appears only in insulating solids. Piezoelectricity can be generated in waxes solidifying under an applied field but the most important group of materials showing the piezoelectricity are crystaline materials.

Piezoelectric effect has to be distinguished from magnetostriction, which is another effect causing a solid dielectric to change the shape on the application of a voltage. In piezoelectric effect the strain reverses the sign when polarity of applied voltage is changed whereas in the magnetostrictive effect the strain does not reverse the sign.

All crystals are anisotropic materials, i.e. do not have the same properties in different directions. According to the molecular structure, the crystals can be classified into 32 classes. From these 20 classes possess piezoelectricity. The criterion that determines whether the crystal is piezoelectric, is possession of the center of symmetry. A crystal which possesses the center of symmetry cannot be piezoelectric because no combination of uniform stresses will produce a separation of the centers of gravity of positive and negative charges and produce an electromagnetic moment necessary for production of polarization by mechanical means. A crystal with no symmetry at all will have 21
elastic constants, 18 piezoelectric constants, and 6 dielectric constants. As the symmetry increases, the number of the constants decreases, until in the most symmetrical type, a cubic one, are only 3 elastic constants, 1 piezoelectric constant and 1 dielectric constant.

The most important crystal for the interferometer use is the quartz crystal. It has advantages against any other synthetic or natural crystal in its high mechanical strength, ability to withstand high temperature and strong piezoelectric properties. A typical quartz crystal can be seen on Fig. 1. It consists of a hexagonal prism terminated at either end by a hexagonal pyramid. This description, however, ignores faces marked x and s, which makes the crystal less symmetrical than the simple hexagonal arrangement. The line joining the vertices of the two pyramids is an axis of symmetry, but the symmetry is not hexagonal but only trigonal, which means that starting from any position it is necessary to rotate the crystal about the axis through one-third of a complete turn before the original pattern is repeated.

Piezoelectric charges in the quartz crystal are produced either by tensile or shear stress. Tensile stress along either X or Y axis liberates charges in the X direction, the electric polarization being equal and opposite for a given stress in these two directions. Shear stresses in the X plane also liberate charges in the X direction, while shear stresses in the Z and Y plane liberate charges in the Y direction. No piezoelectric charges are liberated in the Z direction.

The frequent occurrence of the twinning in quartz crystals necessitates preliminary optical examination of specimen intended for piezoelectric work. Twinning is said to occur when the small components which make up a complete crystal are not all similarly oriented.
**Fig. 1. Quartz Crystal**

**Fig. 2. Oriented Quartz Crystal**

Showing cuts in relation to natural crystal.

**Fig. 3. Transforming Energy - Mechanical energy becomes electrical as force is applied to crystal electrodes.**
The resulting twinned crystal, if well shaped, bears the modification of $s$ and $x$ faces at each edge of the hexagonal prism instead of on alternate edges only.

Due to the reasons mentioned above the most used cut of the crystal for the ultrasonic work is X-cut. The vibration of the plate is induced by means of two thin electrodes fastened to both planes ($x$-planes) of the crystal. The frequency of the vibration of the quartz plate is almost entirely governed by its dimensions, by the type of the vibration and by the orientation of the plate in the original quartz crystal. Variations are also introduced by other factors like temperature or electrode configuration, but these variations are small and we may ignore them when drawing up rules for the prediction to an accuracy of about $0.5$ to $1\%$ of the frequency of the plate of given dimensions.

The natural frequency of a thin plate of thickness $e$ is equal to:

$$\frac{\sqrt{\frac{E'}{\rho}}}{2e}$$

where $E'$ is the elastic modulus corresponding to the type of vibration and $\rho$ is the density. In cases when as here, the frequency is inversely proportional to a dimension of the plate, it is convenient to introduce a "frequency constant" which when divided by the dimension concerned, gives the frequency. This constant is expressed in kilocycle-millimeter/sec. and is denoted by $k$. The value given in literature for $k$ varies between 2830 and 2900 kc-mm/sec.

As it was briefly mentioned above, the piezoactivity varies with the temperature. Ny Tse Ze\(^{(3)}\) reports that it is practically constant
between temperatures 20 and 300°C, but above the upper limit the piezoelectric modulus falls off sharply. The maximum value of the modulus occurs at about 200°C. At about 570°C piezoelectric effect stops completely. Similar conclusion reaches Scheiber(4) who writes that it was impossible to bring a quartz crystal to vibrations in a temperature higher than 500°C. In the region of 400°C the natural frequency change with the temperature is very rapid and so any measurements are impossible without keeping the temperature constant to ± 0.05°C. Evidently the region where the quartz crystal is of practical importance in the interferometry is to about 350°C. For measurements at higher temperatures a provision must be made to keep the crystal cooler.
Theory of Operation of an Acoustic Interferometer

An arrangement of a quartz crystal, reflector or piston connected with an elevating screw and a gas chamber is called an ultrasonic interferometer. A quartz crystal is held between two electrodes on the bottom of the interferometer. A reflecting plate, which can be moved up and down is connected to a micrometer screw outside of the container. The reflector should be exactly parallel with the crystal, the deviation being no more than $1/4$ of the wave-length of used frequency. (2) (7) (9)

If this condition is not fulfilled, a serious distortion of the reflected wave can result. Many earlier workers in ultrasonic interferometry found values for velocity of propagation in non-dispersive gases higher than expected from theory. Experiments and studies by Grabau and Grossman (10) and Grossman (11) showed that these values could be accounted for by a departure of waves from plane parallelism. The crystal and the reflector are placed in a container, where the gas under investigation is admitted.

It is important that the temperature of the gas be kept as constant as possible. Due to the most commonly used $x$-cut of the crystal, its frequency is not independent from the temperature. The variation is comparatively small, but considering the extreme sharpness of the crystal crevasse, the small change in temperature will cause sufficient change in its natural frequency to pull the operating point out of the minimum position on the crevasse.

To operate the interferometer, an oscillator is connected to the crystal and tuned to the natural frequency of the crystal. The vacuum-
tube voltmeter connected across the crystal will register a sharp dip. Movement of the reflector respectively to the crystal will cause the voltage across the crystal to change periodically. A sharp maximum will occur when the distance between the reflector and the crystal is an integral number of half wave-lengths. By counting the number of peaks in a given displacement and measuring the frequency of the crystal, the velocity of the propagation of the sound in the gas can be determined by the relation:

\[
\text{Velocity} = \frac{2 \times \text{displacement}}{\text{No. of half wave-lengths}} \times \text{frequency}
\]

The envelope of the voltage vs. displacement curve consists of two curves approaching each other as the separation between the crystal and the reflector increases. The attenuation of the wave can be calculated from the shape of these curves. The theoretical method of calculating the attenuation was first derived by Hubbard. \(^{(12)}\)
General Description of the Apparatus

To measure the acoustic velocity of steam at high pressure and high temperature, an interferometer of special construction was developed. Figs. 4-7 show the assembled and disassembled views of the interferometer. The interferometer was mounted in an insulated steel tank heated by the superheated steam. A shaft protruding from the bottom of the interferometer through the tank was connected to the driving mechanism. The whole assembly with accessories was mounted in a steel frame. Electric apparatus was assembled in a similar frame to the right of the interferometer. On the left side was located a superheater together with a steam separator. The potentiometer and the accessories for the measurements of the temperature were located on a long bench in the front of the interferometer. The galvanometers for the temperature measurements and crystal voltage recordings were installed on stands built from 4" pipe and bolted to the concrete floor. (Fig. 3)

The supply of the heating steam was obtained from the Institute power plant at approximately 60 lbs. per sq. inch gauge. The steam passed the separator in order to remove excess moisture before it entered the superheater. The superheater was of the gas-fired type with 6 Bunsen burners. To reduce the fluctuations of the gas pressure, a gas pressure regulator was installed in the line ahead of the burners. After leaving the superheater, the steam entered the insulated tank in which the interferometer is housed, and then was discharged to the atmosphere.
The electric apparatus / Fig. 9 / consisted of an "electron" coupled oscillator, tank circuit, Army Signal Corps Frequency Meter Type BC-221L, vacuum tube voltmeter, and galvanometer.

The temperature measurements were made by means of four Chromel-Alumel thermocouples, one of which was mounted directly in the acoustic cavity in the interferometer above the crystal, and three were mounted in the heating tank in different elevations to assure a true mean temperature in the tank. The thermocouples were calibrated in the usual way at the ice point, steam point, and sulphur point.

The pressure gauges used in connection with the interferometer were of laboratory precision type 0-5000 lbs. per sq. inch with subdivisions of 20 lbs. per sq. inch. They were calibrated in the usual manner.

(a) Ultrasonic Interferometer.

The interferometer constructed had to fulfill four major objectives: no leakage at high pressures and elevated temperatures, no sample contamination, ease of operation of the reflector, and a good contact between the crystal and the electrode even at the high temperatures involved, with minimum pressure on the crystal.

The interferometer consists of six major parts as follows: body, cap, ring-nut, lower cap, piston, and bellows with the driving shaft. The cap was machined out, forming thus the upper part of the acoustic cavity. The seal between the cap and the body of the interferometer was formed by a copper gasket. The cap was pressed in place by the ring-nut using a specially constructed wrench fitted in the four milled slots on the top of the cap. This construction, especially the profile of the gasket groove, was found later not to be satisfactory
and the cap with the ring-nut was redesigned. The detail drawing Fig. 5 on page 16 shows the changes made. The main change was made in the shape of the gasket groove, where two concentric rings of the "V" profile were used on the body and two similar rings on the cap, pressing the copper gasket firmly in place. The sealing action at the high pressure was even better, the internal pressure forcing the gasket against the wedge formed by the top and the bottom ring. To facilitate further tightening of the ring-nut, eight vertical holes were drilled and tapped to accommodate 3/8" bolts passing through the ring-nut and contacting an extended lip on the cap. After the cap was tightened with the wrench, the bolts were tightened, thereby increasing the pressure between the cap and the body. The advantage of this arrangement was the ease of the removal of the cap and still having the safety of the screwed connection, the supporting bolts being all the time in compression. The failure of the bolts would still mean no danger of a blown-out cap as this can happen when using a bolted flange.

The cap was drilled on top to accommodate the electrode and the thermocouple connections. Standard high pressure connections with compressed soapstone followers were used for this purpose. The material for the electrode was inconel wire No. 18. The thermocouple wires were of chromel-alumel type. The cap was machined from a solid piece of freemachining stainless steel.

The next main part of the interferometer was the body. This was also machined from freemachining stainless steel. The selection of the material for the interferometer was governed by the consideration that there should be no oxidation at the elevated temperatures and the material still would possess considerable mechanical strength and prevent
ACOUSTIC INTERFEROMETER

FIG. 5.
any rusting due to steam condensate.

The center of the body was drilled out and reamed with a 13/16" spiral reamer to form the lower part of the acoustical chamber. The reflector in the form of the lapped piston was fitted in this chamber. The piston was lapped to the size 0.0004 inches smaller than the cavity to insure a smooth movement and to prevent "binding" while cooling the interferometer to the room temperature. To eliminate any possible piston slap while moving the piston, the length of the piston was made considerably larger than its diameter. To eliminate unnecessary friction between the piston and the cylinder, the middle portion of the piston was machined down to a smaller size. A small groove parallel with the axis of the piston was cut in the piston in order to facilitate the passage of the steam to the lower portion of the interferometer. To obtain a gas-tight seal between the piston rod and interferometer a stainless steel bellows was attached to the lower part of the drive shaft, dividing thus the drive shaft into two parts: the internal portion connecting the piston with the bellows, the external portion connecting the bellows with the driving mechanism. The internal shaft together with the bellows was a standard item, produced by a valve manufacturer and was rated at 400 lb. per sq. inch at 750° Feh. To be able to use the pressures in the excess of ratings, a balancing pressure on the outside of the bellows was needed. Therefore, a cap was fitted over the bellows which joined to the body of the interferometer by a screw connection. The cap was fitted with a conventional packing gland through which the drive shaft extended. A separate high pressure system was designed to supply the equalizing pressure. This system is described on page 25. The small leaks in the equalizing pressure system were not too important, because
the pump was able to supply continuously needed quantities of the water in order to maintain the pressure constant.

The gas could be admitted into the interferometer by a passage drilled in the side of the body perpendicular to its axis. A vertical hole was drilled from the top face of the body to meet the horizontal hole. The previous model of the interferometer had inlet and outlet connections, but it was found that the outlet connection was unnecessary, the air being first evacuated by means of a vacuum pump and then the cavity filled with the water. After finishing the measurements, the gas was evacuated again. As previously stated, the quartz crystal was located directly on the upper face of the interferometer body. To make it possible for the gas to enter the cavity between the crystal and the piston, a 1/16" slot was milled across the face. To keep the crystal from moving in a lateral direction, four ceramic pegs were located, one on each side of the crystal. These pegs were held in place by four brass screws, smaller in diameter than the internal diameter of the ceramic pegs, to allow for thermal expansion of the screws.

The crystal used was of rectangular shape 1 x 1-1/8 in. and approximately 1/8 in. thick. Both the top and bottom surfaces of the crystal were gold plated. The bottom side was placed directly on the plane face of the body, making the connection to the ground. For proper operation of the crystal, the top connection to the crystal has to exert only a very light pressure and should not change with the temperature. The spring electrode used was of the same type as used on previous works of J. Woodburn(1). The form of this electrode can be seen in Fig.6. A small stainless strip of 0.010 in. thickness was hammered down to approximately 0.001 in. thickness and cut to shape. The lower thinner end contacted the crystal,
the upper formed a circular plate and contacted the inconel wire which passed through the cap of the interferometer. The wire was insulated by ceramic tubing. A leakproof connection was made by means of tightly packed soapstone follower compressed by a packing gland.

The inside of the cap contained also a thermocouple. These wires were packed also by soapstone followers and were insulated on the outside of the interferometer by standard "fish-spline" ceramic insulators.

(b) Driving and Recording Mechanism.

The piston of the interferometer was moved by means of a driving mechanism located directly underneath the tank. The shaft extending from the interferometer was secured by a rigid coupling with the shaft of the driving mechanism. The driving mechanism consisted of an elevating screw actuated by a worm and wheel. (Fig. 8). The worm could be turned by hand by means of a knurled knob, or could be motor driven through suitable reduction ratio. By means of a planetary gear system, the hand operation could be changed to motor driven.

The elevating screw was provided with a 12-thread per in. square thread. It was restricted from rotary motion by two small ball bearings contacting two flats machined on the lower end of the elevating screw. This screw was moved vertically by means of a drum-like nut, which could be rotated by the worm-wheel mounted directly on it, but was restricted from the vertical translatory motion by two thrust ball bearings located on the upper and lower faces of the drum.

The motor drive consisted of a high reduction ratio gearing coupled to the worm of the elevating screw. A 1/10 hp. electric variable speed motor was attached to the driving mechanism by means of a "V" belt. The shaft of the driven pulley had a universal joint and was spring
loaded to compensate for the pull of the belt and to prevent the transmission of vibrations from the motor to the driving mechanism.

As it was mentioned before, the reduction gearing was connected to the worm of the elevating screw, but still another output shaft with a slightly different reduction ratio was connected by means of a long shaft to the recording mechanism. This arrangement consisted of a box with a 6 in. diameter brass drum on which a photographic paper was fastened by means of two parallel bars screwed to the cylinder. The front end of the box/ Fig. 3/ contained a narrow slit parallel to the longitudinal axis of the cylinder. The cylinder was attached to the driving shaft through a right angle worm and wheel system. The reduction ratio was chosen so that a vertical motion of the piston of the interferometer of 0.001 in. represented a length of $\frac{1}{8}$ in. on the surface of the drum. A simple coupling was installed in the shaft to facilitate the initial indexing of the drum.

In order to avoid any error due to the irregularities of the driving gears a simple calibrating system was designed. During the run a cathetometer was preset on a series of distances of 0.1 mm apart so that when the piston moved through one of these intervals, a switch could be depressed and an electric impulse sent through an auxiliary lamp in front of the slit on recording drum, which resulted in a mark on the photographic paper. The voltage across the quartz crystal was recorded on the drum by means of a mirror-type galvanometer, using the drum in place of a standard scale.

(c) Heating System.

The heating system consisted of three major parts: separator, superheater, and a tank with the interferometer. The heating steam was taken
from the Institute power plant at about 60 lb. per sq. in. saturated steam. Any excess of water was separated by the separator. Steam then passed through the superheater. This was of a gas-fired type. To obtain the maximum temperature of about 750° Fah. 6 Bunsen type burners were employed. Due to considerable fluctuation of gas pressure a gas pressure regulator was installed in the line.

The superheater consisted simply of a coiled steel pipe placed in a brick furnace. Few bricks were placed inside in the coil to distribute the flame over the entire area. After the steam passed through the superheater, it entered the tank with the interferometer. This consisted of a section of 12 in. pipe with welded hemispherical cap on the bottom and a series of 600 psig. standard flange on the top. A blind flange of the same series was used to cover the tank. The tank was well insulated, a detachable insulation belt being mounted around the flange to facilitate its removal.

The interferometer itself was mounted inside of the tank on three equally radially spaced supports. The three legs of the interferometer contained adjusting screws so that the interferometer could be accurately aligned in the bank. After the driving shaft cleared the packing gland on the bottom of the tank, the interferometer was secured in place by two bolts in each support. These bolts were clamped against each leg of the interferometer from each side.

The steam connection to the interferometer, the thermocouple, and electrode connections passed through the walls of the tank. A standard packing gland was used to seal the steam tubing; the standard soapstone followers were used for the electric connections.

The inlet heating steam pipe was placed in the lower portion of the
tank. The outlet connection was located in the blind flange on the top of the tank. A pressure gauge and a valve were located in the outlet line for adjusting the steam pressure in the tank to its proper value.

Three thermocouple wells were located in the wall of the tank in different elevations to check the distribution of the temperature in the tank. These thermocouples, as also the thermocouple in the interferometer, were of the Chromel-Alumel type and were calibrated before the experiment in the usual manner.

The steam, after passing through the heating tank, was allowed to escape to the atmosphere. A baffle in the steam inlet connection provided ample turbulence and more uniform heating of the interferometer.

As it was mentioned before, the whole assembly including the driving mechanism was mounted in a steel "I" beam frame.

(d) Equalizing Pressure System.

In order to supply equalizing pressure on the outside of the bellows, a supplementary hydraulic system was constructed. Schematically it consisted of a hydraulic pump, supplying water under high pressure into the lower cap of the interferometer. The pump was of a two-stage piston type. The input shaft of the pump was connected by means of a coupling to the variable speed, constant torque hydraulic transmission rated for 2 hp, continuous duty. Later it was found that when using very low pumping speed for a considerable length of time, an external means for cooling oil was necessary. The arrangement of a copper circulating coil and the oil reservoir can be seen from Fig. 8.

The hydraulic transmission was driven by a 1/2 hp. single phase electric motor. The speed was varied by means of a lever on the side of the transmission unit. The range of the output speeds for this type of
transmission is from zero to \(1/3\) of the input speed which was in this case approximately 1800 rpm; output speed 0 - 600 rpm in both directions. The pump, together with the transmission and the motor was mounted on a steel table, independent of the interferometer frame to eliminate any vibrations. A steel supply tank with a filter was also located on the same platform.

Because of the variation in the pressure using single piston pump was considerable, it was necessary to use two hydraulic accumulators in the line to the interferometer. First, a larger one was located directly in the output of the pump; the second, a smaller one was located not far from the interferometer itself. In this manner the line pulsations were reduced to a minimum. In fact they did not exceed 0.1% at 3000 lbs. per sq. in.

A check valve was also installed in the line to protect the interferometer, should the pump fail.

One more very important safety feature was added to the interferometer. This was a blow-out assembly, connected between main and equalizing system. Should the pressure difference between the steam in the acoustic cavity and steam in the equalizing chamber exceed 400 lbs. per sq. in., which is the safe value for the bellows, a membrane in the blow-out assembly will rupture and the pressure difference will equalize. The blow-out assembly consisted of two cylindrical caps bolted together. These caps were bored inside to 3/4 in. in diameter and approximately 1/2 in. deep. A thin brass diaphragm (0.003 in.) was placed between both caps. One end of the blow-out assembly was connected to the main system, one to the equalizing system.

By this method the main system was positively separated from the
equalizing system maintaining the advantage of foolproof protection against excessive pressure differences.

It would be desirable to install a differential pressure gauge across the blow-out assembly, equipped with a minimum-maximum electric contact, so that the motor would start after the pressure had dropped to a dangerous value.

(e) Electrical Apparatus

Electrical apparatus consisted essentially of a variable frequency, "electron" coupled oscillator with the maximum usable range of about from 400 kc to 2 mc, a tank circuit, and a frequency meter. Parallel to the main tuning condenser of the oscillator a small vernier condenser was mounted. This vernier condenser consisted of a hollow brass cylinder and a spindle movable along the centerline of the cylinder. A standard micrometer screw was used for this purpose. The vernier condenser was used for final adjustment of the frequency of the oscillator.

The output of the oscillator was loosely coupled through a tank circuit to the crystal. Thus the amount of electrical energy transferred to the crystal could be varied in a wide range and most suitable power for driving the crystal selected. Usually a potential of one volt across the crystal was found to be sufficient to drive the crystal.

The natural frequency of the crystal was checked by a frequency meter. A short antenna on the frequency meter was loosely coupled to the tank circuit of the oscillator. The oscillator frequency was then superimposed over the frequency of the frequency meter. A zero beat frequency indicated that both oscillators were working on the same or multiple frequencies. The variable frequency oscillator in the frequency meter was calibrated against standard frequency produced by a control crystal.
"ELECTRON COUPLED" TYPE
OSCILLATOR

All resistors are in ohms
1k = 1000 ohms
All capacitors are in μF
1μ = 10⁻⁶ μF

FIG. 9.
Thus the error in frequency determination was guaranteed not to exceed 0.01%.

The power supply for both units received the electrical power from an electronically controlled voltage source. A voltage regulator tube was used in both sets in the plate supply for the oscillator tube. The tube heaters of the frequency meter were operated from a 6-volt storage battery. The heater supply for the oscillator could also be obtained from the storage battery or from above-mentioned voltage regulator. It was found that the results as to the constancy of the voltage using either supply were identical.

During the actual runs it was felt that the constancy of the frequency of the main oscillator was not sufficient to assure trouble-free readings on the recording mechanism. In the future it will be experimented with a feedback from the crystal to the oscillator tube to control the frequency of the oscillator by the crystal itself.
Experimental Method

After the completion of the apparatus much time was spent to eliminate all possible leaks in the interferometer itself and in the inlet piping. After the interferometer was made completely leakproof, another difficulty arose: the stabilization and the distribution of the temperature in the heating tank. The insulation of the tank was found to be insufficient, so that the temperature variation between the top and the bottom of the tank was about 5%. Due to the unequal temperature distribution, the expansion of the interferometer was unequal also and freezing of the piston resulted. The interferometer had to be removed from the tank and the piston re-machined. After the interferometer was again assembled and installed in the tank, it was decided due to the shortage of time not to attempt to bring the interferometer to the high temperature but investigate carbon dioxide gas at room temperature and check the available data on above-mentioned gas under varying pressure.

The experimental procedure for testing this gas is exactly the same as it would be for testing steam. The only difference is the technique of the administration of the tested medium into the interferometer.

A few hours before conducting the experiment all windows in the laboratory were closed in order to stabilize the room temperature as much as possible. The vacuum pump was turned on and the whole system evacuated continuously for about 8 to 10 hours. After that the system was filled with the carbon dioxide to about 300 lb. per sq. in. pressure and evacuated again. This procedure was repeated once more to eliminate possible contamination of the gas with the air.

Meanwhile the electrical apparatus was turned on. The oscillator
was run about two hours on the regular power supply; after that it was
switched to the battery operation. A 6-volt battery was used for the
filament heating of all tubes in the oscillator and a plate battery was
used for the oscillator tube. By this method the frequency drift was mini-
mized. Unfortunately the amplitude stabilization of the oscillator was
unsuccessful. A plate battery could not be used for the two amplifier
tubes following the oscillator tube due to the high power requirements.
This fact did not add to the stability of the amplitude as it can be seen
from curve on page 37.

The only data taken were by photographic means. This method was
found to be considerably faster and more accurate than the manual readings
and will be preferred by all means in the future. It was also found that
the best results were obtained using the mirror galvanometer connected
into the vacuum tube voltmeter circuit in the place of the regular indi-
cator. The response was much faster than by using a vacuum tube thermo-
couple and measuring the current flowing through the crystal.

After the oscillator warmed up, it was tuned to the natural frequency
of the crystal. The natural frequency of the crystal was first calculated
theoretically. Unfortunately the actual frequency of the crystal was
found to differ almost 40% on the lower side. This fact could not be
explained because the actual operating frequency does not seem to be a
harmonic of the theoretical frequency. The calculated frequency was about
850 kc and the actual only 578 kc. It was also found that this is not
only a frequency on which the crystal oscillates. It has few less pro-
nounced crevasses not far from 578 kc. The fact about the inconsistency
of these frequencies is, however, not too important because it does not
affect the results.
Finding the natural frequency of the crystal requires considerable patience. The crevasse is extremely sharp and could be easily overlooked tuning the main condenser of the oscillator. However, after the frequency was found for the first time, the position of the condenser was noted and finding the frequency later became a routine job.

After the crevasse was found and the crystal set to its approximate natural frequency, the vernier condenser of the oscillator was adjusted to exact value of the natural frequency.

The frequency was checked against the frequency meter. The piston of the interferometer was moved in a position between two peaks and the frequency of the oscillator adjusted again to give a minimum deflection on the voltmeter. After that, the mirror galvanometer was connected into the vacuum tube voltmeter circuit and the projection of the slit on the light source focused on the recording drum.

The deflection of the galvanometer was compensated by a d.c. voltage supplied by the vacuum tube voltmeter. No calibration of the deflection of the galvanometer in c.m.f. units was attempted. After the photographic paper was installed on the recording drum, the piston was moved into extreme upper position and the automatic drive engaged displacing the piston downward.

The drum was calibrated against the movement of the driving shaft by a standard micrometer. The micrometer was fixed on the driving shaft and a constant tension device attached to it so that by moving the shaft, the micrometer continued to be in contact with the ball mounted on the support. By this arrangement a continuous reading was possible.

The temperature measurement was done two times during the runs using the thermocouple and potentiometer. After few trial runs the time
necessary for one run was estimated to be about 5 minutes, including the change of the pressure in the interferometer and also change of the photographic paper in the recorder.
Results and Conclusions.

As it was stated above, no data were taken on superheated steam. In order to try out the apparatus few runs were made on CO\textsubscript{2} at room temperature. Unfortunately again the time was short for any extensive measurements. Four points at different pressures were measured. Two runs were made at lowest pressure, only one run for each succeeding pressure. Each run contained one recorded curve of e.m.f. on the crystal vs. displacement of the reflector. About 10 to 11 peaks on each curve were used for computations. Great precision of these data was not expected, because these were trial runs made in one session and no time was allowed for any corrections or compensations.

The shape of these curves is satisfactory at pressures higher than 60 lbs. per sq. in., but shows considerable variation in lower region. One cause is instability of the frequency and amplitude of the oscillator, second cause may be due to small variation of the temperature in the interferometer itself. The crystal is extremely sensitive to temperature variations and a change as small as +0.02°C will produce a shift in the crevasse strong enough to change the deflection of the galvanometer.

The consistency of readings has probably no meaning in this case because, as it was mentioned above, the points were not checked by a second run. The standard deviations of mean values were calculated but these again do not represent a true picture, because still the mean value can be off by an unknown amount.

The results in tabulated and in a graph form are presented on page 35.

These results are compared with two available data of Hodge\textsuperscript{(12)} and Herget\textsuperscript{(13)}. Both authors were concerned with relatively high pressures
SONIC VELOCITY IN CO₂

as a function of pressure at constant temperature 29.4°C.

FIG. 10.
and their data on lower pressures contains only few points. From the
graph it is evident that their data differ a considerable amount, even
if both claim an accuracy of +0.2%.

It is also evident that the measured curve has in general a different
slope than the other two. No conclusions can be drawn because no points
were taken further toward higher pressures. It is possible that the last
point is in error and the curve is flatter than it is represented on the
graph. It is expected that investigating higher pressures a closer corre-
lation can be obtained.

It is clear that photographic method offers far more accurate means
of evaluating the acoustic velocity than any other method.

It has to be remembered that these data were obtained only in one
run, whereas data obtained by manual method in one run will vary con-
siderably.

It is true that this photographic recorder at the present time is
far from being perfect. A constancy of used frequency and constancy of
the driving speed are necessary for perfect recording. Also the inertia
of the mirror-type galvanometer must be kept small, so that perfect
tracing of the curve is obtained.

But even the recorder as it is now is a helpful means of obtaining
data on high pressures where a crevasse of crystal becomes very shallow
and peaks lose their sharp definitions due to increased damping produced
by gas under high pressures.
Data on Carbon Dioxide at Temperature 29.4°C (x)

<table>
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<tr>
<th>Pressure at Abs.</th>
<th>Velocity ( \text{m/sec.} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.08</td>
<td>272.8±7.2</td>
</tr>
<tr>
<td>9.02</td>
<td>269.4±0.9</td>
</tr>
<tr>
<td>14.60</td>
<td>263.3±2.3</td>
</tr>
<tr>
<td>22.10</td>
<td>256.2±1.7</td>
</tr>
</tbody>
</table>

**NOTE**

The possible error is expressed in terms of standard deviation. The measurement of temperature is considered as exact, only variation being in observing pressure and displacement.

The frequency measurements are assumed to be exact. A possible variation of ±0.01% in frequency will have a negligible effect upon acoustic velocity.

(x) The gas investigated was commercially pure. No additional purification or dehydration was attempted.
APPENDIX

OBSERVED DATA

Notes and Explanations for Following Pages:

1. All errors are expressed in terms of standard deviation.

2. Scale factor represents ratio of actual movement of reflector of interferometer to linear distance on the recording drum.
Pressure: 74.7 ± 2.5 psia = 5.08 ± 0.17 at abs.

Temperature: 29.4 ± 0.01°C

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<tr>
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<th>Δ</th>
<th>Δ²</th>
<th>Peak No</th>
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<th>Δ²</th>
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Scale Factor: \( \frac{5 \text{ actual ins.}}{573 \text{ recorded ins.}} \)

Mean \( \lambda/2 \) (from both runs) + 1064 ± 28

\( \lambda = 0.047165 \pm 0.00124 \text{ cm.} \)

\( \rho = 578.46 \text{ kcy.} \)

\( v = 272.8 \pm 7.2 \text{ m/sec.} \)
Pressure: 132.7 ± 2.5 psia = 9.02 ± 0.17 at abs.

Temperatures: 29.4 ± 0.1°C

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Scale factor: 5 actual ins. 573 recorded ins.

Mean $\lambda/2 = 1050.9 \pm 3.3$

$\lambda = 0.04658 \pm 0.00015$ cm.

$f = 578.46$ kcy.

$v = 269.4 \pm 0.9$ m/sec.
Pressure: 214.7 ± 2.5 psia = 14.60 ± 0.17 at abs.

Temperature: 29.4 ± 0.1°C

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Scale factor: 5 actual ins. 
573 recorded ins.

Mean value of \( \lambda/2 = 1026.8 \pm 8.5 \)

\( \lambda = 0.045526 \pm 0.00039 \) cm.

\( \varepsilon = 578.38 \) key

\( v = 263.3 \pm 2.3 \) m/sec.
Pressure: 324.7 ± 2.5 psia = 22.10 ± 0.17 at abs.

Temperature: 29.4 ± 0.1°C

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Scale factor: \( \frac{\text{5 actual ins.}}{\text{573 recorded ins.}} \)

Mean value of \( \frac{1}{2} \) = 999.1 ± 6.7

\( \gamma = 0.04429 \pm 0.00030 \) cm.

\( f = 578.41 \) kcy.

\( v = 256.2 \pm 1.7 \) m/sec.

**NOTE:**

Mean computed for readings 2 through 8.
Rest of readings neglected. For reasons see \( \Delta^2 \) column and curve 4 on Fig. 11.
BIBLIOGRAPHY

(1) Woodburn, J.: An Experimental Determination of the Velocity of Sound in Superheated Steam


(7) Alleman, R. S., Phys. Rev. 1939.


