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The Dielectric Constants of Air and Hydrogen at High Pressures

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The dielectric constants of air and hydrogen at pressures from 71.8 to 334.7 atmospheres at 20°C have been measured. The values were obtained by measuring, with a capacity meter of the heterodyne type, the variation with pressure of the capacity of a fixed condenser fitted into the pressure vessel. The frequency was 2500 kilocycles. The dielectric constants obtained are slightly lower than those of Tangl and Broxon for pressures about 80 atmospheres. The Clausius-Mosotti function $(\epsilon-1)/d(\epsilon+2)$ was calculated for each pressure. The change with pressure for air is small and irregular, average 1.43. For hydrogen the value decreased uniformly from 1.16 at 71.8 atmospheres to 0.99 at 334.7 atmospheres.

INTRODUCTION

THE development of a differential manometer for use with hydrogen and air over the pressure range 1 to 340 atmospheres in which the deflection of a diaphragm changed the capacity between attached condenser plates, required that the dielectric constant of the gases be known. Measurements of the dielectric constant of air have been made to the pressure of 170 atmospheres; while for hydrogen, some work has been done on pressures to 194 atmospheres. The dielectric constant of air at pressures up to 170 atmospheres has been determined at low frequencies or by static methods by Tangl,[1, 2] Waibel[3] and Broxon.[4] Jordan, Broxon and Walz[5] have made measurements of the dielectric constant of air at pressures up to 170 atmospheres and at frequencies of 1 to 70 kilocycles. Occhialini,[6] using a frequency of about 10,000 cycles, obtained results which were lower than those of the other workers mentioned here.

DESCRIPTION OF APPARATUS

A fixed air condenser was made to fit into a pressure vessel and variation of capacity of this condenser with pressure was measured with a capacity meter of the heterodyne type, operating at a frequency of 2500 kilocycles.

The gas, from a Rix compressor, was cooled to about 15°C and passed through a baffle-plate type separator and then through a filter consisting of six inches of tightly packed felt. This arrangement removed all of the oil and lowered the water concentration to 0.015 percent. Moisture determinations were made by drying samples over Desic-chora. After the filter, the gas flowed through a coil of 1.5-millimeter diameter copper tubing where it was brought to room temperature, which was kept constant (±1°C) throughout the entire series of measurements. A cylindrical steel pressure vessel, having inside dimensions of 9 cm diameter by 6 cm, was connected through appropriate valves to the tubing. A Bourdon type gauge which, for this work, had been calibrated on a dead weight tester was in the line. The accuracy of the pressure measurements was at least one percent.

The condenser shown in Fig. 1 was fastened to the bottom of the pressure vessel and the electrical lead to it carried through an isolantite bushing in the top of the steel shell. A spring attached to the bushing made contact with the top plate of the condenser.

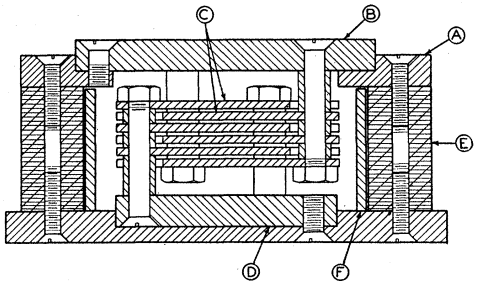

FIG. 1. Condenser construction.

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[1] Karl Tangl, Ann. d. Physik **23**, 559 (1907).

[2] Karl Tangl, Ann. d. Physik **26**, 59 (1908).

[3] F. Waibel, Ann. d. Physik **72**, 161 (1923).

[4] James W. Broxon, Phys. Rev. **37**, 1338 (1931).

[5] A. R. Jordan, J. W. Broxon and F. C. Walz, Phys. Rev. **46**, 66 (1934).

[6] A. Occhialini, Physik. Zeits. **6**, 669 (1905).

In order to make correction for the effect of solid insulation, the condenser was built so that the parallel condenser plates, upon which the change in capacity with pressure was determined, were isolated from the solid insulation by means of shielding and could be removed from the frame of the condenser and replaced without change in capacity. This was accomplished by mounting the condenser plates *C* on end plates *B* and *D* which were in turn fastened to the frame of the condenser in such a way that the entire assembly of condenser and end plates could be removed from the frame as a unit. The top ring of the frame was insulated from the bottom plate by four isolantite posts *E* which were shielded from the condenser plates by the cylinder *F* fastened to the bottom plate and separated from the top plate by a 0.3-millimeter gap.

Capacity meter

The high frequency heterodyne type capacity meter, shown in Fig. 2, was used in which the unknown capacity acted as the tuning condenser of the "manometer oscillator" which employed a modified Hartley circuit. The plate end of the oscillatory circuit was grounded and current was carried to the tube filament through the double-wound coil L_4–L_5. This circuit required the use of only one bushing through the shell of the pressure vessel and allowed the base of the condenser and the shielding to be fastened directly to the grounded shell.

Another oscillator, which also acted as a detector, was coupled to the manometer oscillator by means of a low impedance link circuit. This consisted of single loops coupled to the oscillator coils connected by a twisted pair, one conductor of which was grounded. The standard Hartley circuit was used in this detector unit. An accurate vernier dial on the tuning condenser C_1 gave a maximum accuracy of one part in one thousand. C_2 is a trimming condenser used to adjust the range of the capacity meter. Both units were shielded by means of heavy copper boxes.

The beat note between the oscillators could be heard in the telephone receivers connected in the plate circuit of the detector-oscillator unit. Zero beat, the setting where the frequencies of the two oscillators were exactly equal, was the point at which readings were made. The use of a moderately high frequency, two to three megacycles, the stability of the oscillators and the very loose coupling between them minimized the effect of "pulling in" to such an extent that the zero beat method could be used without difficulty. Since both the oscillators were connected to the same power supply the factors which would cause the frequency of an oscillator to drift would cause both to drift the same direction by the same amount. This would not affect the frequency differences and consequently changes in plate and filament potential and variation in temperature had little effect on the calibration. This apparatus was built rigidly enough so that there could not be any change of its calibration because of mechanical distortion of its component parts.

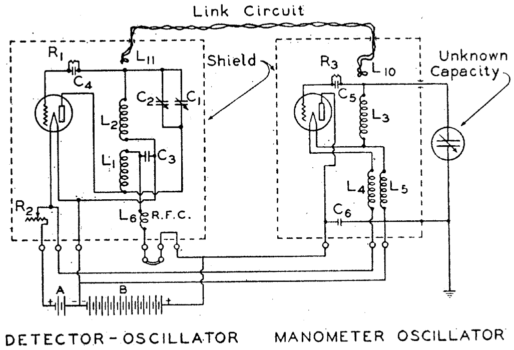

FIG. 2. Circuit for the high frequency heterodyne capacity meter.

EXPERIMENTAL PROCEDURE

The capacity meter was calibrated against a General Radio Type 222 precision condenser. This condenser was substituted for the unknown capacity and readings made at frequent intervals on the scale. Calibrations were made after each set of dielectric measurements and the maximum difference between corresponding points on the various calibrations was found to be less than 0.2 percent. As a further check on the calibration, a second variable condenser was placed across the standard condenser and the lower end of the standard condenser scale checked against other sections by means of the capacity meter.

Air or hydrogen at 340 atmospheres was

slowly released into the pressure vessel which contained the fixed condenser. At intervals of about 70 atmospheres, the inflow of gas was stopped and the capacity of the condenser was measured. The system was allowed to stand at each pressure until the capacity remained constant, although the change that did occur at first was negligible. After the maximum pressure had been reached, the measurements were repeated with decreasing pressure.

The pressure vessel was then opened and the plate assembly removed from the condenser. A blank cover plate of exactly the same dimensions as the top plate B Fig. 1, was put on the frame and the pressure vessel again closed. The gas was run in and capacity measurements made for each pressure in the manner previously described. These measurements gave the variation with pressure of the capacity of the condenser frame, solid insulation, contact spring, and shielding.

When the condenser is assembled with the plates in, it may be considered to consist of the capacity between the plates, the dielectric of which is entirely air, in parallel with the capacity of the shielding, frame, insulation, etc., some of which are solid dielectrics. The dimensions of the exterior of the condenser were exactly the same whether the blank cover plate or the plate B were in, so that the capacity between the condenser and pressure vessel was the same in both cases. Therefore, the difference between the capacities with the plates C in and with them out represented the capacity of these plates with each other and with the surrounding shielding. No solid insulation was in the field of this capacity. Consequently the variation, with change in pressure, of this difference C_0-c_0 where,

C_0 = capacity at 1 atmosphere with plate C in,
c_0 = capacity at 1 atmosphere with plate C out,

was a capacity on which the solid dielectric of the condenser had no effect.

One of the difficulties encountered in this circuit was the change in reactance of some of its components with the change in capacity of the condenser inside the pressure vessel. The worst offender in this respect was the bushing through the pressure vessel shell. The value of C_0-c_0 was measured with the condenser outside of the pressure vessel and found to be 2.0 mmf less than the value of C_0-c_0 for the condenser when in the pressure vessel. A variable condenser was placed across the terminals of the capacity meter, the ungrounded lead of which ran through the bushing. The apparent capacity of the bushing was then measured for various settings of the condenser. Between the capacity settings corresponding to c_0 and C_0, respectively, the capacity of the bushing was found to increase 2.0 mmf. This accounts for the discrepancy in the values of C_0-c_0. Correction was made for this variation in the results. The error introduced by the difference in resistance between the standard and substituted condenser when the bushing was not in the circuit was in the order of 0.005 percent, which could be neglected. The mechanical strength required of a bushing to withstand such high pressures requires a type of construction in which the electrical losses are high and the reactance variable.

In the dielectric constant determination of air the accuracy of $(\epsilon-1)$ was about one percent of the maximum value while for hydrogen the accuracy on this basis was about two percent.

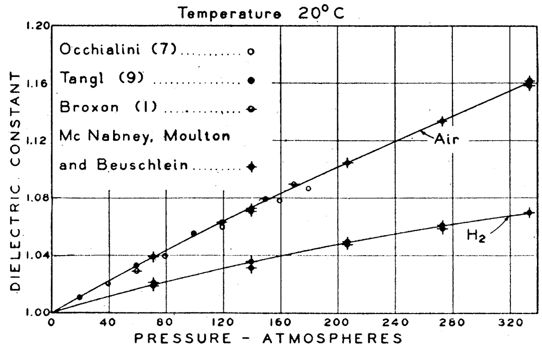

FIG. 3. Dielectric constant of air and hydrogen as a function of pressure.

TABLE I. *Dielectric constants of air and hydrogen.* Frequency 2.5 megacycles. Temperature 20°C.

Press. (Atmos.)	Air Dielectric constant (ϵ) Run 1	Run 2	$\left(\frac{\epsilon-1}{\epsilon+2}\right)\times\left(\frac{1}{d}\right)10^4$*	Hydrogen Dielectric constant (ϵ) Run 1	Run 2	$\left(\frac{\epsilon-1}{\epsilon+2}\right)\times\left(\frac{1}{d}\right)10^4$
72.0	1.039	1.039	1.47	1.019	1.021	1.16
140.0	1.073	1.071	1.40	1.032	1.036	1.07
208.0	1.106	1.105	1.41	1.048	1.050	1.05
274.0	1.134	1.134	1.42	1.059	1.061	1.00
335.0	1.162	1.159	1.45	1.070	1.070	0.99

* Values of d were calculated from I.C.T.

Since the dielectric constant of air at one atmosphere (ϵ_1) is 1.00059, the dielectric constant at pressure P is given by the equation,

$$\epsilon_P = [(C_P - c_P)/(C_0 - c_0)](\epsilon_1).$$

The values of the dielectric constant determined for the various pressures are given in Table I and are shown graphically in Fig. 3. The measurements for air obtained with ascending and descending pressures checked exactly. The data for hydrogen were obtained with descending pressures only. This showed that there was no hysteresis effect. Data on the compressibility of isolantite were not found in the literature. An estimate of the error due to the compressibility was made by using data given for soapstone, a similar material. The displacement of the plates at 350 atmospheres pressure was estimated to be 0.3 percent of the plate spacing, causing a change in capacity of less than 0.05 percent. The values so obtained are slightly lower than those of Tangl and of Broxon for pressures above 80 atmospheres, and the slopes of the curves decrease slightly as the pressure increases for both air and hydrogen. According to the Clausius-Mosotti equation:

$$[(\epsilon - 1)/(\epsilon + 2)](M/d) = \text{constant};$$

ϵ = dielectric constant; M = molecular weight; d = density. The Clausius-Mosotti function $[(\epsilon - 1)/(\epsilon + 2)]/d$, was calculated for each pressure and is shown in the tabulated results. In these results, the change in the Clausius-Mosotti function with pressure for air is small and irregular, while for hydrogen the function decreases with increase in pressure.

The curvature of the pressure-dielectric constant line for air may be due either to an effect of the high frequency at high gas densities, or to some irregularity in the operation of the capacity meter. Jordan, Broxon and Walz,[5] using the apparatus of Broxon[4] showed that the change of dielectric constant of air with frequency was very small over the pressure range 1 to 170 atmospheres and a frequency range of zero to 70 kilocycles. The experimental results for air shown in Fig. 3 fall below those of Tangl[1, 2] and of Broxon[4] and above those of Occhialini.[6] The frequency used in this work was 2.5 megacycles while Talbot[7] working at a pressure of one atmosphere found no appreciable change in the dielectric constant over the frequency range of 0.025 to 1.100 megacycles. The frequency and some of the pressures used in this experimental work are beyond the range of the above determinations.

Broxon[4] has compared the results of dielectric constant determinations found in the literature and has concluded that those made at high frequencies are not consistent among themselves while those at low frequencies are in agreement. Cagniard[8] pointed out that many of the investigators using high frequency methods had difficulty with instability of their oscillating circuits. No instability was encountered in the apparatus described in this paper; but, as has been previously mentioned, other factors may have caused apparent changes in capacity. Further research in the measurement of capacities at high frequencies is desirable because the heterodyne capacity meter, using high frequency oscillators, has characteristics which make its use advisable, and sometimes necessary for many practical applications of capacity measurements.

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[7] F. L. Talbot, Thesis in Physics, Catholic University of America, Washington, D. C., 1928.

[8] L. Cagniard, Ann. de Physique **9–10**, 460 (1928).