A capacitive pressure gauge as a reliable transfer pressure standard

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Abstract

This paper describes the performance of an alternative capacitive pressure gauge using lead iron tungstate as a capacitive element over a pressure range of 418 MPa. A commercial strain gauge pressure transducer is used to get the consistency in the calibration equation of the pressure transducer using the piston gauge pressure standard when compared with the calibration equation of the pressure transducer obtained using the capacitive pressure gauge. A close agreement better than $1 \times 10^{-3}$ (overall accuracy of the pressure transducer is $\pm 5 \times 10^{-3}$) demonstrates for the first time the use of the capacitive pressure gauge as a reliable pressure standard where the required accuracy in the pressure measured is below $1 \times 10^{-3}$.

Keywords: Transducer, Pressure measurements, Pressure standards, Hydraulic pressures

1. Introduction

The measurement of hydrostatic pressure has traditionally been performed in most national metrological laboratories through the use of liquid column manometers and piston gauges, generally regarded as first principle instruments [1–5]. In general, a primary pressure standard establishes a pressure scale in terms of force per unit area without resorting to calibration against the other pressure standards of higher accuracy. However, when a piston gauge is used as a secondary standard, its effective area is determined by comparison against another piston gauge of known effective area or against a mercury manometer. A piston gauge is successfully used over a medium range of pressures up to 280 MPa, and is serving as a reliable, portable and reproducible pressure transfer standard to promote the uniformity in the pressure measurement. It also helps to trace out the possible systematic errors, if any, in the pressure measured by the standards established in different metrological laboratories. These gauges, if required to be used beyond 280 MPa, become bulky and expensive both to purchase and operate, and can not be transported easily. This seriously limits their utility.

The pressure transfer standard useful in the high pressure region measures pressure in terms of some other suitable physical property whose relation to pressure is determined by a calibration, i.e. by comparison with an instrument of higher accuracy. A wide choice of physical properties, which vary with pressure, is available for their exploration as pressure transducer [6]. Though a large variety of high-pressure transducers are available, only the manganin resistive transducer [7] is extensively used as a pressure transfer standard (in the high-pressure region). Of late, other strain gauge transducers are also beginning to be used and indeed calibrated strain gauge transducers [8] are commercially available to measure pressures up to a GPa. Though these gauges are in use, these are handicapped with zero shift with time, hysteresis, low pressure cut-off and limited sensitivity; and hence need frequent calibration against the primary pressure standards. It thus implies that one has to find out an alternative pressure transducer wherein these effects should be minimized, if not eliminated completely.

Efforts have been made for quite some time to understand the pressure dependence of relative permittivity through the variation of capacitance with applied
pressure. The studies of capacitance as a function of the applied pressure on a few crystalline and poly-crystalline materials [9–11] have revealed their limited pressure coefficient and relatively large temperature coefficient of capacitance. It was only recently that the present authors carried out dielectric studies as a function of applied hydrostatic pressures on lead based ferroelectric relaxors [12,13], thereby demonstrating their usefulness in pressure gauging. Ferroelectric relaxors have been known for many years for their unique properties like high relative permittivity, broad maxima, relatively low firing temperatures with nearly zero thermal expansion and low aging effect, etc. These properties make them attractive for a number of applications like multilayer layer capacitors, actuators, and piezo-transducer and in medical ultrasonics, etc. [14–17]. These studies [12,13] have thus added one more application of the ferroelectric relaxor, as a pressure gauge, in the already existing long list.

In the present investigation, the systematic studies of the capacitance and the dielectric loss are carried out on lead iron tungstate (PFW) as a function of the applied high hydrostatic pressure ranging from 0.1 to 418 MPa, and at temperatures ranging from 291 to 393 K, respectively. The experimental data of the relative permittivity ($\varepsilon_r$) as a function of the applied pressure is expressed in the form a second order polynomial calibration equation of a pressure transducer (herein after designated as transducer). The results of an independent calibration of a transducer against a laboratory piston gauge pressure standard and the PFW capacitance pressure gauge over a pressure region up to 418 MPa are reported here.

2. Experimental

The specimens of PFW were prepared using high purity oxides (PbO, 99.9%; Fe$_2$O$_3$, 99.5%; and WO$_3$, 99.99%, from Aldrich, USA) by the conventional solid state sintering method. All of the sintered disks of 18 mm in diameter and 1.4–1.8 mm in thickness were polished and silver electrodes with a guard ring on one face of the disk were deposited by vacuum evaporation, using a special mask. With the given specimen dimensions, the width of the guard ring was suitably adjusted to ensure that there was no fringing effect [9].

A specimen was placed in a specially designed cell that can be pressurized directly to a maximum of 600 MPa. The capacitance and the dissipation factor were measured at a fixed frequency of 1 kHz using an automatic digital capacitance bridge with an accuracy of ±0.1 ppm in the capacitance range of interest. For estimating the hysteresis, observations were made over a complete pressure cycle, i.e., first by increasing and then by decreasing the pressure at the same temperature. The pressure is transmitted through diethyl hexyl sebacate fluid as it does not react with the specimen, and its viscosity does not change appreciably over the pressure range of interest. The pressure was measured with accuracy better than ±0.03%. The cell was immersed in a constant temperature bath capable of maintaining temperature within ±0.05 K during measurement. The temperature of a specimen was measured with a chromel–alumel thermocouple placed just near the specimen using a digital temperature indicator having a resolution of 0.01 K. The pressure effect on the chromel–alumel thermocouple and the consequent temperature correction are quite small for the conditions in the present experiment.

The dead weight piston gauge [18] used as a secondary pressure standard is equipped with a simple-type piston and cylinder assembly having a full-scale pressure of 500 MPa. The effective area and the pressure coefficient of the piston-cylinder assembly of the gauge were estimated in the laboratory by calibrating the secondary standard against primary controlled clearance pressure standard that has a full pressure range of 500 MPa. The value of 3σ uncertainty (99.7% confidence level) obtained for secondary standard is ±300 ppm.

The strain gauge transducer of 1.4 GPa (full scale) has a sensitivity of 0.02 mV MPa$^{-1}$. The overall accuracy of the pressure measured by the transducer was ±5 × 10$^{-3}$ (full scale). The input voltage was supplied with a highly stabilized DC power supply and its output was measured with an autoranging digital multimeter having a resolution of 10 µV.

3. Results and discussions

3.1. Capacitive pressure gauge

The relative permittivity was calculated from the capacitance measured directly by the capacitance bridge without considering the compressibility of the specimen, as in the present case only a relative change in the permittivity is meaningful. The relative permittivity of PFW as a function of applied hydrostatic pressure as calculated at 1 kHz while increasing the pressure in steps arbitrarily fixed at 49, 96.5, 142.5, 189, 235, 280.5, 326, 373 and 418 MPa, respectively and decreasing the same from 418 MPa to atmospheric pressure, are plotted in Fig. 1. At each pressure point, three observations were made, and three such complete pressure cycles were carried out under identical conditions. It is observed that the relative permittivity ($\varepsilon_r$) decreases nearly linearly with the increase of applied pressure. The relative permittivity was also calculated at different temperatures and at atmospheric pressure. From the above observation, the average values of the pressure and
temperature coefficients of relative permittivity ($\varepsilon_r$) are calculated as $-530 \times 10^{-12}$ Pa and $-0.007$ K, respectively. The behavior of relative permittivity studied as a function of temperature is observed to follow the same pattern, and the absolute value of $\varepsilon_r$ decreases understandably with an increase in the temperature of a specimen above transition temperature.

In all of the pressure cycles, the observed small hysteresis reduces to zero when the applied pressure exceeds 200 MPa. Total hysteresis effect in all the three cycles lies between $2.48 \times 10^{-4}$ and $3.80 \times 10^{-4}$, whereas its magnitude varies from $3.46 \times 10^{-5}$ to $3.29 \times 10^{-4}$ in a cycle. The maximum zero shift, reference taken as before starting the calibration cycles, was always less than 0.5 pF over the entire pressure range. This is well below 0.1% of the full scale of the capacitive element and is sufficiently below the expected uncertainty of the capacitive gauge. The typical short term reproducibility in any of three cycles varies from $2.18 \times 10^{-7}$ to $1.49 \times 10^{-8}$ with pressure increasing up to 418 MPa and from $2.91 \times 10^{-7}$ to $6.91 \times 10^{-7}$ with pressure decreasing to atmosphere. The relative permittivity value of 1074, as calculated at 1 kHz and at 302 K, can not be compared directly as the earlier reported values, are at low temperatures (153–253 K) and at higher frequencies [19,20]. It may be mentioned that this is the only reported work describing variation of $\varepsilon_r$ with pressure in PFW and at high temperature. The value of dielectric loss is measured to 0.006. The low loss is desirable for a reproducible gauge. Comparing these results with the most commonly used manganin resistive transducer which has the pressure and temperature coefficient of $23 \times 10^{-12}$ Pa and 500 $\mu$Ω K$^{-1}$ around 300 K, and a hysteresis of the order of $1 \times 10^{-4}$. This shows that the capacitive pressure gauge is certainly at an advantageous position over the conventional transducers.

The best least square fit, using all of the data of the three pressure cycles over a pressure range 20–418 MPa obtained as a second order interpolation equation

$$P(\text{MPa}) = 3289.155 - 5101.145X + 1814.404X^2$$

$$\sigma = 0.481 \text{ MPa}$$

where $X = \varepsilon_r / \varepsilon_{ao}$, where $\varepsilon_r$ is the value of relative permittivity at any pressure $P$ and $\varepsilon_{ao}$ is its value at atmospheric pressure) is the output of the capacitive element, corrected for its value at atmospheric pressure.

4. Calibration of strain gauge pressure transducer

In order to visualize the performance of the capacitance pressure gauge under reference, the transducer is first calibrated against the piston gauge pressure standard and then against the capacitive pressure gauge. Three pressure cycles at 302 K were taken on different days in the pressure range up to 418 MPa. At each pressure point, three observations were made.

The best least square fit, using the data of all three pressure cycles over the pressure range 49–418 MPa obtained as a second order interpolation equation

$$P(\text{MPa}) = 0.330021 + 707.0366X - 21.90383X^2$$

$$\sigma = 0.138 \text{ MPa}$$

where $X$ = mV V$^{-1}$ is the output of the transducer corrected for zero.

![Graph](image)

Fig. 1. Pressure dependence of relative permittivity of PFW in combined three pressure cycles of one of the capacitive element at 1 KHz and at 302 K: △, first cycle; ○, third cycle.
Fig. 2. Deviation in the pressure calculated from the calibration equation of the strain gauge pressure transducer obtained from its calibration against the laboratory piston gauge pressure standard from the pressure value calculated using the calibration equation obtained against capacitance pressure gauge.

The transducer is again calibrated against the capacitance pressure gauge over the pressure range up to 418 MPa at 302 K, following the above mentioned procedure. The best least square fit, using all the data of all the three pressure cycles over the pressure range 49–418 MPa obtained as a second order interpolation equation

\[ P(\text{MPa}) = 0.931044 + 702.4893X - 15.08775X^2 \]
\[ \sigma = 0.293 \text{ MPa} \]

(3)

where \( X \) = mV V\(^{-1}\) is the output of the transducer corrected for zero.

The pressure difference calculated using the two independent calibration equations (Eqs. (2) and (3)) of the transducers were of the order of \( 6.6 \times 10^{-4} \) at the full scale of 418 MPa and this difference is represented graphically in Fig. 2. Considering the stated uncertainty in the pressure measured by the laboratory piston gauge pressure standard, and the accuracy of the individual transducer and capacitance pressure gauge, the agreement is excellent. The capacitance pressure gauge under reference can be used as a reliable pressure gauging instrument where the pressure are to be measured within an accuracy of \( \pm 1 \times 10^{-3} \) on the conservative basis. Efforts are being made to further improve its accuracy of measurement by lowering its hysteresis, aging effect and increasing its long-term stability.

5. Conclusion

A close agreement with in \( 6.6 \times 10^{-4} \) between the calibration results of the strain gauge pressure transducer calibrated against the piston gauge pressure standard and the capacitive pressure gauge is observed over the whole pressure range. This demonstrates the use of the capacitive pressure gauge as a reliable pressure transfer standard where the estimated accuracy of \( \pm 1 \times 10^{-3} \) or below is required in the pressure measured.

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References


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