Atomic Standard of Pressure

NIST will determine the pressure p(ε,T) of helium gas by measuring and calculating the dielectric constant, ε (p,T). Ultimately, the uncertainties from the theory, impurities, and the electrical and temperature measurements are expected to be smaller than those of existing pressure standards (piston gauges). When this occurs, the dielectric constant of helium will become the basis for a new pressure standard. The standard will be disseminated by calibrating piston-cylinder sets and by using the helium standard to measure ε (p,T) of argon. Argon is chosen becauseit is readily available in high purity and because its dielectric polarizability is eight times larger than that of helium.

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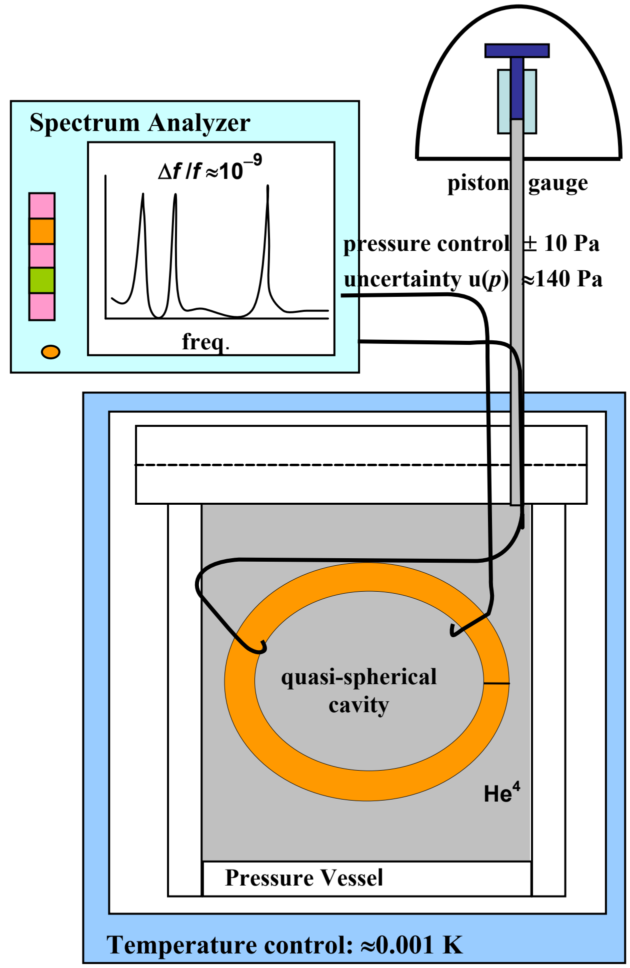
Below 300 kPa, the primary pressure standard at NIST is a 3-meter mercury manometer. Above 300 kPa, the pressure standards are commercially manufactured piston-cylinder sets. These sets are complicated artifacts. In operation, the cylinder and piston deform significantly and the piston rotates continuously to ensure gas lubrication. Because of these complications, piston-cylinder sets are calibrated using the primary-standard mercury manometer below 300 kPa, and their performance is extrapolated to higher pressures using numerical models of the coupled gas flow and elastic distortions. However, this extrapolation cannot be verified using existing technologies; thus, it is not fully trusted. Furthermore, piston-cylinder sets exhibit poorly understood species and gas flow dependencies. When $\varepsilon\,(p,T)$ of helium becomes the pressure standard, it will be possible to test models of piston-cylinder sets and to reduce the uncertainty in the assignment of their effective area.

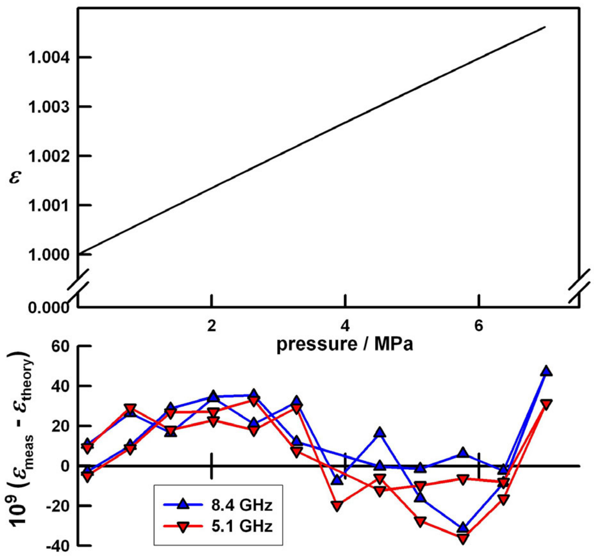
The NIST goal is to develop an accurate primary standard for pressure in the range 0.3 MPa to 7 MPa based on fundamental physical properties of helium. This program will revolutionize the realization of pressure standards.



A schematic drawing of the apparatus is shown above. We use this design to measure $\varepsilon\,(p,T)$, the dielectric permittivities of helium and argon, in the ranges 0.1 MPa to 7 MPa and 0 °C to 50 °C. We determine $\varepsilon\,(p,T)$ from measurements of the temperature, pressure, and microwave resonance frequencies of a gas-filled quasi-spherical cavity. The cavity's shape differs from that of a perfect sphere by only a few parts in one thousand. This small distortion is just enough to lift the triple degeneracy of the lowest microwave resonance frequencies, thereby facilitating frequency measurements with part-per-billion uncertainties.

The helium-filled microwave cavity is bounded by walls made of copper-plated maraging steel. The theory must account for the shrinkage of these walls (and the cavity) under applied pressure. We calculated the shrinkage from the isothermal compressibility k_T of maraging steel samples cut from the same billet as the walls. We determined k_T of maraging steel with an uncertainty of 0.1 % by measuring the frequencies of the mechanical resonances of the cylindrical samples. This is an advance in the state-of-the art of resonance ultrasonic spectroscopy.

The graphs show the measurements of ε (p,23°C) of helium and the deviations of the measured values from the theoretical values. The values measured as the pressure increased and as the pressure decreased for two resonance modes (5.1 GHz and 8.4 GHz) are mutually consistent to 8×10^{-9} (standard deviation). The measured values differ from the theory by 20×10^{-9} (standard deviation). The results for ε (p,T) obtained with a quasi-spherical microwave cavity have 20 times the resolution of measurements made with the capacitance bridge used in previous measurements.



Top Graph: ***The dielectric permittivity of helium as a function of pressure measured with the ellipsoidal microwave resonator.***
Bottom Graph: ***Deviations of measured dielectric constant from theory in parts per billion.***

Impacts:

This program will revolutionize the realization of pressure standards.

We discovered that gas-filled, quasi-spherical cavities are excellent acoustic thermometers. NIST is using them to determine the imperfections of the internationally-accepted temperature scale, ITS–90.

We used existing equipment to measure ε (p,T) of the primary constituents of natural gas (CH_4, C_2H_6, C_3H_8, N_2, CO_2, Ar) as well as O_2 and H_2 in the temperature range 0 ºC to 50 ºC and at pressures up to 7 MPa. These data are more accurate than any previous data; they comprise reference data for metering the heating value of natural gas.