The Emerging Field of Quantum Based Measurements for Pressure, Vacuum and Beyond

J Hendricks¹, Z Ahmed¹, D Barker¹, P. Egan², K Douglass¹, S Eckel¹, J Fedchak¹, N Klimov¹, J Ricker¹, J Scherschligt¹, J. Stone²

National Institute of Standards and Technology, Physical Measurement Laboratory, ¹Sensor Science Division, Thermodynamic Metrology Group, ²Engineering Physics Division, Dimensional Metrology Group, 100 Bureau Drive, Gaithersburg, MD 20899-8363
E-mail: jay.hendricks@nist.gov

Abstract. The future of pressure, vacuum and even temperature measurement will employ lasers, Fabry-Perot optical cavities, cold atom traps and lots of quantum physics. For pressure measurement of a gas, photons interact at the quantum level such that light travels at a slower speed in gas than it does in vacuum. For extreme vacuum measurements, cold atom traps will be used to detect single collisions between gas trapped cold atoms enabling the number density of the gas to be measured. For temperature measurement is performed using silicon photonics to detect the small changes in refractive index in micro machined silicon photonics coupled to optical fibers. For dynamic pressure, NIST is developing a method where the unique quantum mechanical characteristics of the molecules are themselves the standard for pressure, making it consistent with the quantum-SI. Our approach is to use independent molecular spectroscopy as a dynamic measurement of pressure, where the pressure and temperature is ascertained by measuring time-resolved pressure-broadened spectra of CO molecules. This paper briefly reviews the status of these projects currently underway at the NIST Thermodynamic Metrology Group.

1. Introduction

For pressure measurement of a gas, photons interact at the quantum level such that light travels at a slower speed in gas than it does in vacuum. NIST is developing a fixed length optical cavity (FLOC) and variable length optical that will make simultaneous ultra-precise measurements of vacuum and gas cavity photon-path lengths. While pressure is a widely measured unit in everyday processes, the standard on which it is based, the mercury manometer is quite old and traces its early beginnings to 1643. In the future, the mercury barometer will be replaced with a new standard based on quantum chemistry calculations. [1-4]

2. The Fixed Length Optical Cavity

An optical cavity consists of a set of mirrors on a spacer with the gas filling the space between the mirrors. To improve upon this design, you can add a reference cavity that is kept at vacuum to help eliminate noise and other systematic errors. This design, referred to as a Fixed Length Optical Cavity (FLOC), was constructed and is shown in Figure 1. The FLOC was constructed out of a glass with very low thermal expansion to prevent changes in interferometer length with temperature. The upper cavity consists of a slot to allow gas to easily flow in and out where as the reference cavity is a hole drilled through the glass block and sealed at either end via mirrors.

Additionally, a vertical tube allows us to pump out the reference cavity through a vacuum pump. The glass cavity is placed inside a chamber to improve temperature stability and to ensure that the gas species is known, and therefore has a known refractivity. For gasses such as helium with simple electron structure and limited number of isotopes, the refractivity and density virial coefficients can be calculated through quantum mechanics [2]. This calculation can provide refractivity to an uncertainty better than 1 parts in 10⁶. For other gasses, the values must be measured or will be calculated but with significantly larger uncertainties. Because the calculation of...
pressure is only dependant on refractivity and temperature, we can define the FLOC as a primary realization of pressure.

Even though the FLOC is primary, it does contain two critical drawbacks that must be accounted for when making a high accuracy measurement. The first of which is the distortion of the glass as you apply pressure. The glass experiences a bulk compression as you apply a force to the outside surfaces. In addition to the bulk compression, the glass experiences a non-uniform bending because the reference cavity is at a different pressure and the glass experiences non-uniform forces. The distortions are different for each glass cavity; however, the correction can be determined experimentally and corrected with some uncertainty. The second drawback is that helium can absorb into glass causing the glass to swell. With good interferometer data the absorption can be traced over time and extrapolated back to zero, however this does have some associated uncertainty.

Overall a FLOC standard can achieve an uncertainty of 9 parts in 10⁶ in nitrogen [4], however a better determination of index would allow this to be drastically reduced. Additionally, the best method to measure pressure distortions would be to use several gasses of known refractive index at the same pressure. The distortions will be independent of gas species and can be solved to determine the magnitude of the error. This may introduce uncertainty if the refractivity is not determined precisely, so better refractivity measurements lead to better pressure standards.

3. Cold Atoms Vacuum Standard (CAVS/CCT)
NIST is developing new a method for measuring and understanding the pascal at the lowest pressures, the Cold-Atom Vacuum Standard (CAVS) which uses a cold atom trap to sense pressure. [5] This work began in earnest in 2016. Since the earliest days of neutral atom trapping, it has been known that the background gas in the vacuum limits the trap lifetime (the characteristic time that atoms remain trapped). We are inverting this problem to create a quantum-based standard and sensor. Because the measured loss-rate of ultra-cold atoms from the trap depends on a fundamental atomic property (the loss-rate coefficient, related to the thermalized cross section) such atoms can be used as an absolute sensor and primary vacuum standard. Researchers have often observed that the relationship between the trap lifetime and background gas can be an indication of the vacuum level, and several research groups have pursued using cold atom traps as vacuum sensors. [6,7] However, an absolute vacuum standard, sufficient for use as an international quality standard, has not yet been realized. To do this requires rigorous attention to all potential error sources, from both the atomic perspective and the vacuum perspective. Moreover, a primary CAVS requires the collision cross section between trapped ultra-cold atoms and the background gas to be traceable to an ab initio theoretical determination. NIST has built a laboratory-scale CAVS apparatus, developed the measurement scheme, and done preliminary theoretical calculations, all of which show promising early results. In addition, we are developing a small, portable version that uses a grating-based trap (shown in the Figure 2) that will eventually enable users to realize and measure vacuum pressures in their lab without relying on calibrated sensor artifacts. [8]

4. Silicon Photonic for Temperature Measurements and SPOT
Temperature measurements play a crucial role in various aspects of modern technology ranging from medicine and manufacturing process control, to environmental and oil-and-gas industry. Among
various temperature measurement solutions, resistance-based thermometry is a time-tested method of disseminating temperature standards [9]. Although industrial resistance thermometers can routinely measure temperatures with uncertainties of 10 mK, their performance is sensitive to multiple environmental variables such as mechanical shock, thermal stress and humidity. These fundamental limitations of resistance thermometry, as well as the desire to reduce sensor ownership cost have ignited a substantial interest in the development of alternative temperature measurement solutions such as photonics-based temperature sensors [10,11]. NIST is developing novel on-chip integrated silicon photonic temperature sensors with nanoscale footprint and ultra-high resolution as an alternative solution to legacy-based resistance thermometers. These sensors are Fabry-Perrot cavity type silicon photonic devices that are based on photonic crystal nanobeam cavity (PhCC), whose high-Q resonant frequency mode is highly sensitive to even ultra-small temperature variations. We performed the first direct comparison of our photonic thermometers to Standard Platinum Resistance Thermometers, the best in class resistance temperature sensors used to disseminate the International Temperature Scale of 1990. The preliminary results indicate that our PhCC nanothermometers are capable of detecting changes of temperature as small as sub-10 μK and can achieve measurement capabilities that are on-par or even better than the state-of-the-art resistance thermometry.

5. Dynamic Pressure using Molecular Spectroscopy
From measuring pressures in internal combustion engines to deployment of air bags, to understanding the concussive forces of a blast on a battlefield the measurement of transient pressure is critical to a variety of safety and industrial applications yet there exists no pathway for traceability. NIST is developing a method where the unique quantum mechanical characteristics of the molecules are themselves the standard for pressure, making it consistent with the quantum-SI. Our approach is to use independent molecular spectroscopy as a dynamic measurement of pressure, where the pressure and temperature is ascertained by measuring time-resolved pressure-broadened spectra of CO molecules.[12, 13] Figure 4 illustrates the temperature and pressure dependence of R(7) at v = 2<sub>2</sub> of carbon monoxide near 4288 cm<sup>-1</sup> (2331 nm). Carbon monoxide is chosen for its very strong transition moment and large spacing between ro-vibrational transitions, which will enable resolved measurements up to several megapascals with relative concentrations of CO of only a few percent. The transient pressure source for these measurements is based on a recently constructed and characterized a dual diaphragm shock tube that allows us to achieve shock amplitude reproducibility of approximately 2.3% for shocks with Mach speeds ranging from 1.26 to 1.5.[14] The agreement to 1-D modeling over this limited range is within a few percent and we believe a limiting factor in assessing the 1-D model is the inherent limitation of the piezo electric sensors used to determine Mach speed of the propagating shockwave. To overcome these challenges, we are developing phonic sensors that have extremely fast rise times (ns) and very small sensing area (100 μm). The plots shown in Figure 4 illustrate R(7) at v = 2<sub>2</sub> of CO. The left panel shows a pressure dependant linewidth of experiment (colors) to HITRAN
simulation (model) at room temperature and pressures from atmospheric to 1 MPa. The right panel illustrates temperature dependence of the intensities at 1 MPa from room temperature to 673 K.

Figure 5: Dynamic Pressure Modeling Results along with Data from NIST Shock Tube

6. Conclusions

These emerging technologies will have profound impacts on how measurements of pressure, vacuum, XHV, and temperature will be made in the future. The benefits to the metrologist is the direct traceability to the SI. The benefits to industry is the ability to create new products that require numerous sensors for new applications that are emerging in new high-technology products that are light weight, fast, and inexpensive to manufacture. While these applications are still in the future, looking for new methodologies to make measurements that are photonically based is likely to be instrumental. The NIST Thermodynamic Metrology Group has demonstrated that pressure, vacuum, temperature, and dynamic pressure, measurements can be made using photonic based measurements.

References

[1] P. Egan, J. Stone, J. Hendricks, J. Ricker, G. Scace, G. Strouse, “Performance of a dual Fabry–Perot cavity refractometer,” Opt. Letters, Vol. 40, No. 17, August 2015.

[2] M. Puchalski, K. Piszczatowski, J. Komasa, B. Jezierski, K. Szalewicz, 2016, “Theoretical determination of the polarizability dispersion and the refractive index of helium,” Amer. Phys. Soc., Phys. Rev. A.

[3] P. Egan, J. Stone, J. Ricker, J. Hendricks, 2016, “Metrology for comparison of displacements at the picometer level,” Amer. Inst. of Phys., Rev. of Sci. Inst. 87, 053113.

[4] J. Stone, P. Egan, J. Hendricks, G. Strouse, D. Olson, J. Ricker, G. Scace, D. Gerty, 2015 “Metrology for comparison of displacements at the picometer level,” Key Eng. Mat. Vol. 625 p 79-84.

[5] J. Scherschligt, J. A. Fedchak, D.S. Barker, S. Eckel, N. Klimov, C. Makrides, and E. Tiesinga, Metrologia 54, S125 (2017).

[6] D.E. Fagnan, J. Wang, C. Zhu, P. Djuricanin, B.G. Klapauff, J.L. Booth, and K.W. Madison, Phys. Rev. A - At. Mol. Opt. Phys. 80, 1 (2009).

[7] T. Arpornthip, C.A. Sackett, and K.J. Hughes, Phys. Rev. A - At. Mol. Opt. Phys. 85, 1 (2012).

[8] S. Eckel, D. Barker, J. Fedchak, N. Klimov, E. Norrgard and J. Scherschligt, Metrologia (submitted 2018).

[9] Strouse, NIST Spec. Publ. 250, 81 (2008).

[10] Kim et al., Opt. Express 18, 22215 (2010).

[11] Klimov et al., Proc. SPIE 9486, 948609 (2015).

[12] Douglass, K.O. and D.A. Olson 2016 Towards a standard for the dynamic measurement of pressure based on laser absorption spectroscopy. Metrologia. 53(3): p. S96-S106.

[13] Ahmed, Z., D. Olson, and K.O. Douglass 2016 Precision Spectroscopy to Enable Traceable Dynamic Measurements of Pressure. CLEO: p. ATu1J.1.

[14] Hanson, E., et al. 2018 Towards traceable transient pressure metrology. Metrologia.