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Status and performance of the LNE-Cnam Fabry-Perot refractometer

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INDEX WORDS

Fabry-Perot, refractometry, fixed-length optical cavity, force-balanced piston gauge, optical pressure standard.

***Abstract* – We present the status of the single-cavity Fabry-Perot interferometer developed at the LNE-Cnam laboratory used for thermodynamic pressure measurements within the range of 100 Pa to 100 kPa. After characterizing the intrinsic parameters of the refractometer, this optical sensor is used to measure the refractivity of nitrogen. Then, using the Lorentz-Lorenz equation and knowing the refractive virial coefficients at 532 nm, it is possible to deduce its density. Measuring the temperature of the gas makes it possible to determine its pressure using an equation of state.**

Once the temperature and pressure stability of the gas inside the optical sensor have been achieved at sub-mK and mPa levels, respectively, the expanded uncertainty of the sensor is evaluated to be $[(50\ \mathrm{mPa})^2 + (22 \times 10^{-6} \cdot p)^2]^{1/2}$. In order to further decrease this uncertainty, several approaches and solutions are given, leading to more accurate and reliable pressure measurements.

The developed optical cavity operates as a high-resolution pressure sensor with an objective of complementing and eventually replacing conventional pressure standards, such as the force-balanced piston gauge and capacitance diaphragm gauge, that are based on the classical definition of pressure.

I. INTRODUCTION

The most accurate pressure measurement in the low-pressure range (≤ 100 kPa) has been performed by pressure standards that are based on the mechanical (classical) definition of pressure [1]. However, when it comes to covering a wide pressure range from 100 Pa to 100 kPa, several instruments should be used. Each pressure standard operates within its own limited range, and their corresponding uncertainties tend to degrade as the pressure decreases, as illustrated in Fig 5. Moreover, the National Metrology Institutes (NMIs) do not foresee any progress on this point. Consequently, several NMIs have been attracted to alternative methods such as optical thermodynamic pressure measurement technique using a Fabry-Perot interferometer (FP). This approach, which do not rely on mechanical actuators, offers the advantage of covering the entire pressure range of interest with lower uncertainties, especially below 10 kPa [2]–[5].

II. OPTICAL PRESSURE ASSESSMENT VIA FREQUENCY MEASUREMENTS

When a laser beam is frequency locked on a FP resonant mode TEM_{00}, which occurs due to the constructive interference of the optical waves inside the cavity, any change in the gas refractivity is tracked by the laser frequency at the same rate in order to maintain the resonance [4].

The assessment of gas refractive index n using the optical sensor is performed by measuring the frequency of the laser locked on the FP cavity under vacuum ν_0 and under gas ν_g, while taking into account the correction linked to the physical deformation of the cavity. This can be expressed by:

$$n - 1 = (1 + \epsilon_a)\frac{\nu_0 - \nu_g + \Delta m \cdot \Delta\nu_{FSR}}{\nu_g} + n(-\alpha\Delta T + \beta\Delta P + \gamma\Delta t), \tag{1}$$

where, α is the coefficient of thermal expansion, β is the pressure-induced distortion coefficient, γ is the cavity long-term drift, ϵ_α is the mirror dispersion phase shift, $\Delta\nu_{FSR}$ is the free spectral range and Δm is the number of resonant modes of the FP between vacuum and gas conditions. The terms ΔT, ΔP and Δt represent, respectively, the temperature difference, the pressure difference and the time elapsed during the transition of the cavity from the vacuum state to the gas state [6], [7].

For a real gas that is subjected to both two- and three-body interactions (nitrogen), the molar density ρ can be related to the gas refractive index n according to the extended Lorentz-Lorenz equation as follows [7]–[10]:

$$\frac{n^2-1}{n^2+2} = \rho(A_R + B_R\rho + C_R\rho^2 + \cdots), \qquad (2)$$

where, A_R is the dynamic molar polarizability, B_R and C_R are the second and third refractivity virial coefficients of the gas, respectively.

According to the equation of state for a real gas, the thermodynamic pressure P is a function of molecular density ρ and temperature T as follows [8]:

$$P = \rho RTZ = \rho RT\left(1 + B_\rho\rho + C_\rho\rho^2 + \cdots\right), \qquad (3)$$

where R is the (ideal) gas constant (which is given by the product of Avogadro number N_A and Boltzmann constant k), B_ρ and C_ρ are the second and third density virial coefficients, respectively.

III. EXPERIMENTAL SET-UP

The single cavity Fabry-Perot refractometer, cubic in shape with a 50 mm edge length, developed at the LNE-Cnam laboratory, is shown in Fig 1.

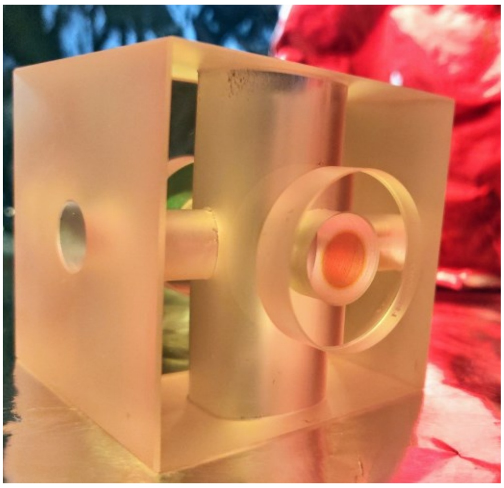

Fig 1. Single Fabry-Perot cavity developed at LNE-Cnam.

The spacer of the FP cavity is made of Zerodur® class 0, chosen for its low coefficient of thermal expansion, given by the manufacturer to be $1.6 \times 10^{-8}/\mathrm{K}$. In addition, this material is selected for its high resistance to helium permeation, if this gas is to be used [11]. On this Zerodur® block, two fused silica mirrors, coated with a dielectric layer resulting in a reflection coefficient of (99.97 ± 0.01) % at 532 nm, are optically bounded.

This interferometric pressure sensor is placed within a series of copper and stainless-steel enclosures (Fig 4.), which serve to isolate the cavity from external disturbances, especially temperature fluctuations. Furthermore, three temperature control systems are implemented on the copper enclosures to stabilize the refractometer's temperature to a sub-mK level around the gallium melting-point (Fig 2), which is the calibration temperature of the Pt25 sensor used for gas temperature measurement.

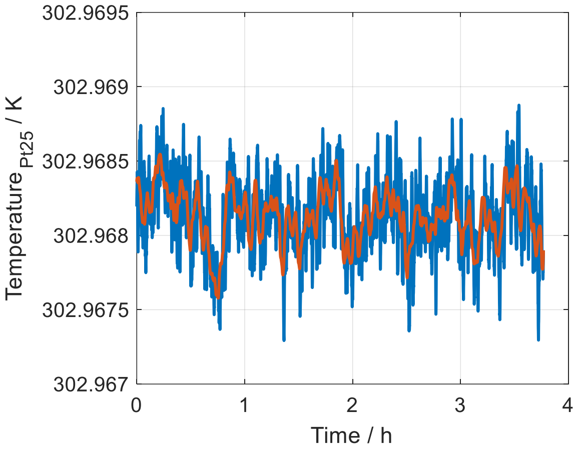

Fig 2. Temperature of the refractometer measured by the calibrated Pt25 sensor.

This temperature, which is measured by the calibrated Pt25 sensor, shows a standard deviation of 0.3 mK during a measurement period of nearly 4 hours. Over a week of temperature measurements, the maximum variation is found to be less than 1 mK.

To ensure nitrogen pressure stability in the interferometric sensor, a PG7607 reference pressure balance is used, with an extended uncertainty of $0.2\ \text{Pa} + 9.0 \times 10^{-6} \cdot p$ ($k = 2$). An example of nitrogen pressure stability at 60 kPa using this reference pressure standard and its measurement by the developed FP is shown in Fig 3.

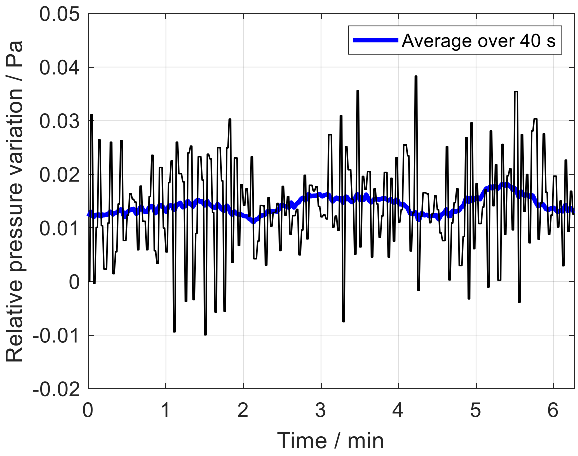

Fig 3. Relative pressure measurement at 60 kPa using the refractometer.

The pressure measurement shows a standard deviation of 1.6 mPa. This corresponds to a variation of 0.03 ppm of the measured pressure. This means that the refractometer is more sensitive than any mechanical pressure gauge in this pressure range. In other words, in this configuration, relative pressure measurement using the FP is limited by the pressure stability of the PG7607.

The optical pressure is measured with respect to a reference pressure state in which the Fabry-Perot cavity is under vacuum. The frequency resolution in this case is about 100 Hz, corresponding to a pressure variation of 65 µPa.

In the measurement (gas) or reference state (vacuum), the laser frequency is locked on a resonant mode of the FP interferometer (Fig 4). This locked frequency is then measured by beating frequency against another similar Nd:YAG laser (reference laser), operating at 532 nm, whose frequency is locked on a hyperfine component of an iodine molecular transition, ensuring high accuracy [12]. The deduced frequency of the "measurement" laser makes it possible to determine the thermodynamic pressure of the nitrogen inside the refractometer using equations (1), (2), and (3).

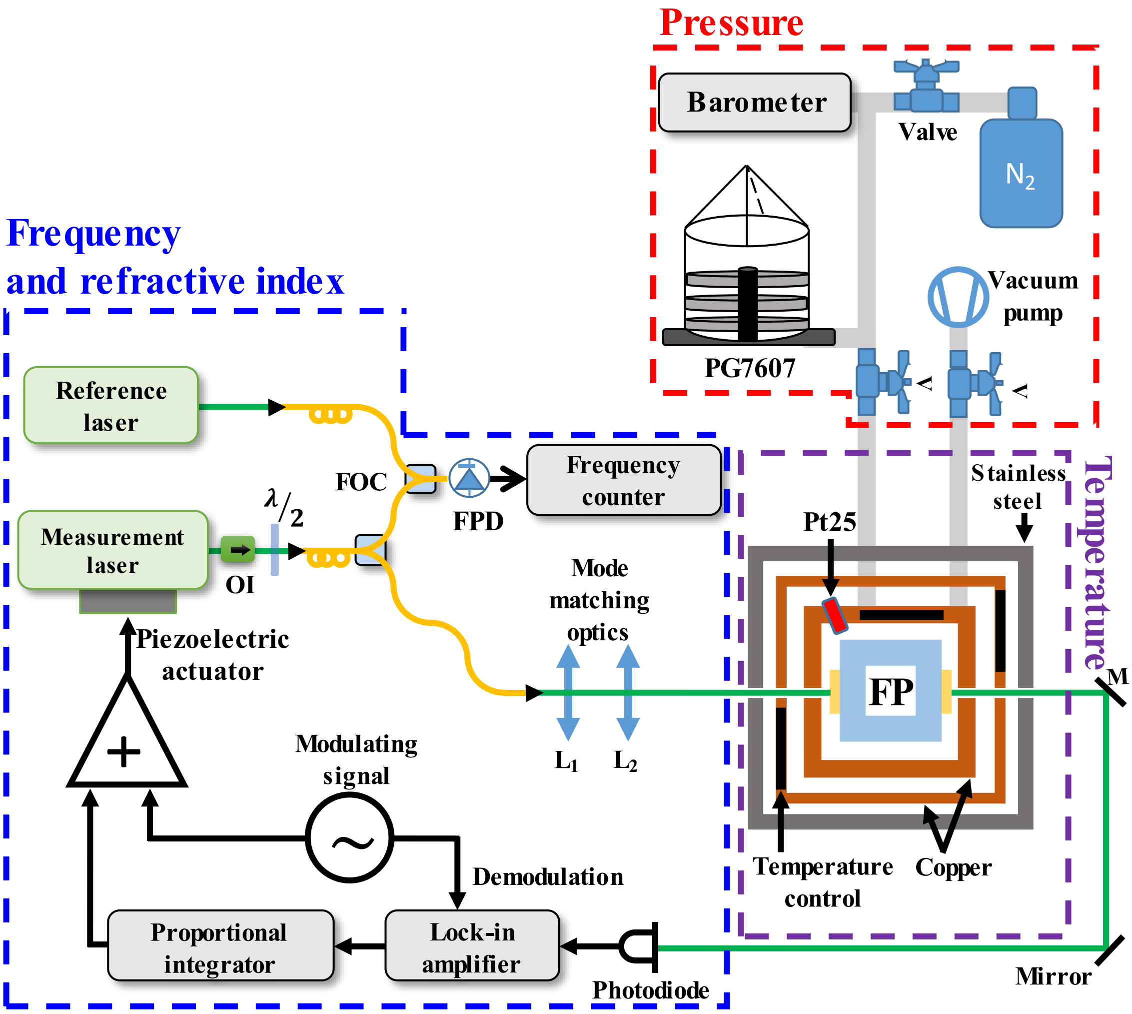

Fig 4. Optical system for pressure measurement: Components include: Optical Isolator (OI), Fiber Optical Couplers (FOC), Lens (L), and Fast Photo-Detector (FPD).

IV. COMPARISON WITH REFERENCE PRESSURE STANDARDS

After measuring all the intrinsic parameters of the refractometer and extrapolating the density and refractivity virial coefficients of the nitrogen at a wavelength of 532.2 nm and a temperature of 302.966 K, the extended uncertainty of the Fabry-Perot cavity for thermodynamic pressure measurement is estimated to be $[(50\,\mathrm{mPa})^2 + (22 \times 10^{-6} \cdot p)^2]^{1/2}$ ($k = 2$).

The Fig 5 illustrates the comparison between the claimed uncertainty of the Fabry-Perot interferometer, which measures optical pressure using atomic properties of gases, and the reference pressure standards based on the mechanical definition of pressure (at $k = 2$), which are known to achieve the highest level of accuracy in pressure measurements to date.

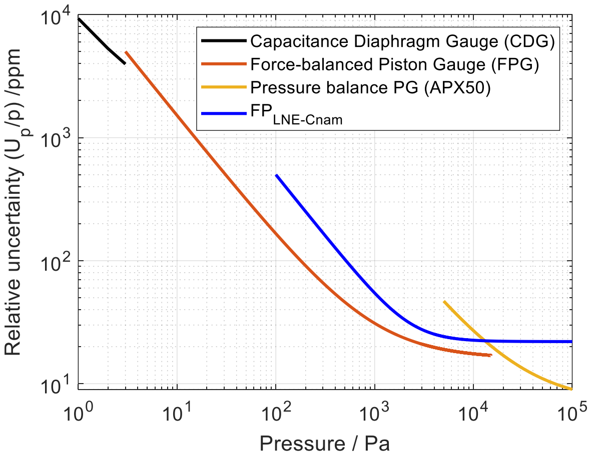

Fig 5. Relative uncertainty comparisons of optical and mechanical pressure standards.

The first assessment of the uncertainty of the optical sensor developed at LNE-Cnam, covering the pressure range from 100 Pa to 100 kPa, demonstrates a closeness to the uncertainties associated to mechanical pressure standards, with the aim of exceeding them. These advances indicate that optical interferometers could eventually replace the current mechanical standards, facilitating the emergence of new optical pressure standards.

To mitigate uncertainties at high pressures, efforts can be made to minimize the uncertainties associated with factors such as the pressure-induced distortion coefficient, the measured temperature, the second density virial coefficient and the molar polarizability of nitrogen at 532 nm (which are currently extrapolated from literature sources [5], [7]). In this way, the pressure-proportional term of the PF uncertainty can be reduced.

To reduce the uncertainties for relatively low pressures, the fused silica mirrors should be replaced by materials with a lower coefficient of thermal expansion such as Zerodur® or Ultra-Low Expansion. This will reduce the uncertainty of the coefficient of the thermal expansion of the FP cavity and the uncertainty of the ΔT parameter. In addition, efforts should be made to reduce and minimize the outgassing effect. Improving these factors will reduce the offset term of the uncertainty associated to the FP.

V. CONCLUSION

The Fabry-Perot interferometer developed at the LNE-Cnam laboratory demonstrates operational pressure measurement capabilities. Achieving such promising uncertainty level is due to a complete characterization of all intrinsic parameters of the refractometer, complemented by sub-millikelvin temperature stability and the utilization of high-purity nitrogen.

It is possible to achieve lower uncertainties associated to the refractometer by lowering the current sources of uncertainty. To achieve this, several solutions are suggested. These include replacing the fused silica mirrors, improving temperature measurement under vacuum conditions, and re-evaluating the molar polarizability of nitrogen at 532 nm and the pressure-induced distortion coefficient using the two-gas method. By addressing these factors, it becomes possible to effectively reduce the overall uncertainty in pressure measurements.

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