A laser interferometric oil manometer as the primary standard for absolute pressure in the range 1 – 1000 Pa

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Abstract. The paper describes the principle and research of a new laser interferometric oil manometer for measuring low absolute pressure, which is being developed at the D.I. Mendeleyev Institute for Metrology (VNIIM). Surface waves in oil are effectively suppressed with specially designed floats supporting the thin near-surface layer in manometer tubes. A new approach to the research of capillary uncertainty is proposed. It is based on interferometric measurements of the oil surface curvature in manometer tubes and allows a correct estimation of the capillary uncertainty. Today the total uncertainty of the measured pressure \( P \) is estimated to be \((1.0 + 0.01p/\text{Pa}) \cdot 10^{-2} \text{ Pa.}\)

1. Introduction
According to the results of key comparison CCM.P-K4 (2002) [1] interferometric mercury U-tube manometers are the most accurate primary standards for low absolute pressure in the range 1 – 1000 Pa. In spite of well-known advantages of using oil as a manometric fluid (low density and vapour pressure) oil manometers do not find the wide-spread application till now. The unique ultrasonic oil manometer (UIM) in NIST [2] has low enough upper limit about 140 Pa perhaps due to high attenuation of sound in oil. There is a problem of accurate measurements of sound speed in oil, which has a significant temperature dependence besides. The main problem of the laser interferometric oil manometers (LIOM) is to suppress the fluctuations of free oil surface, caused by vibrations in laboratory. Its well-known solution for mercury manometers, floats with retro-reflectors of cat’s eye type [3], seems to be not appropriate to oil ones for some reasons. In the unique LIOM NRLM [4] the air-suspension of the device had been used for this aim. In the earliest optical oil manometers the surface waves had been damped owing to very small thickness of oil column (about 0.5 mm) [5-7] so the range of pressure measurements was very narrow - about 5-6 Pa. In [8] special design of floats had been suggested to expand pressure range to 1000 Pa at the least.

2. Description
Figure 1 shows the operating principle of the LIOM. The U-tube 1, which is made from glass cylinders and closed with flat optical windows 2, contains about 200 ml of the oil (mark VM-1) 3 for diffusion vacuum pumps. The free surfaces of the oil are serving as mirrors of the Michelson’s interferometer 4, which is illuminated by frequency-stabilized He-Ne laser 5. The fringes are detected with two photo-diodes 6 and counted with interface scheme 7 and computer 8.
Figure 1. Operating principle of the LIOM: 1 - U-tube; 2 - optical windows; 3 - the oil; 4 - interferometer; 5 - He-Ne laser; 6 - photo-diodes; 7 - interface scheme; 8 – computer; 9 – polarizer; 10 - half mirror; 11 – prism; 12 - polarization beam splitter; 13 - teflon cup; 14 – pins; 15 – holes; 16 - glass sealed cylinder; 17 - glass drop.

After evacuation the both limbs (measuring and comparative) of LIOM to residual pressure about $p_0 = 10^{-4}$ Pa, the pressure change in measuring limb causes the shift of interferometric fringes and can be evaluated as

$$p - p_0 = \rho \cdot g \cdot \frac{N \cdot \lambda}{2}$$

where $p$ and $p_0$ are the gas pressure values in the measuring and comparative limbs of the manometer, $\rho$ is the density of the oil, $g$ is the acceleration of gravity, $N$ is the number of counted fringes and $\lambda$ is the wavelength of laser.

2.1. Features of the optical system

The laser beam passes through the complementary polarizer 9, which is oriented at 45° to the plane of the drawing. Passing the half mirror 10 and the left limb, it reflects twice in the prism 11 and so receives the polarization near to circular. The second beam remains linearly polarized. Thus the polarization beam splitter 12 and photo-diodes 6 in the output of the interferometer form two interference signals with phase difference about 90°, that is necessary for reversible fringe counting.

The very low reflectivity of the oil surfaces and polarization losses provide the intensity of light returned to the laser low enough not to disturb its stabilization system.

2.2. Wave-damping system.

The design of special floats is shown in Figure 1. The float consists of two parts. The upper part of the float is the teflon cup 13 with external radius, that is 1 mm less than radius of the manometer tube, and three pins 14, that stabilize its coaxial position with the tube. The cup bottom is flat inside and is cone-shaped from below to let air bubbles exit free when oil is being degassed. The cup has three small holes 15 near walls providing the penetration of the oil inside. The lower part of the float represents a glass sealed cylinder 16 with three glass pins on the top bearing the teflon cup, and six
pins directed radial to stabilize its vertical position inside a tube of the manometer. The size of the parts is chosen to ensure the necessary thickness of the oil layer (about 0.5 mm) in the float. The immersion depth of the float is easily adjusted by changing the ballast glass drop 17, soldered to the bottom part of the glass cylinder.

The investigations have shown such a construction of the floats to reduce fluctuations of free oil surface about two orders of magnitude (from 2-3 to 0.01-0.03 fringes) thus permitting interferometric measurements in a wide range of pressure.

3. The uncertainties of LIOM

The main sources of uncertainty in pressure measurements for the LIOM (Equation 1) are well-known. The contribution of laser wavelength and acceleration of gravity to the systematic uncertainty is less than 1 ppm.

3.1. The oil density.
The value of the oil density ($\rho = 873.03 \text{ kg/m}^3, t = 20.0^\circ \text{C}$) was measured in VNIIM by the secondary standard of density with uncertainty of about 10 ppm. But there is a problem to correct this value for dissolved air and compressibility of the oil. It was not required in [2] because oil UIM had been calibrated with the help of mercury UIM. We couldn’t find any data in literature on this problem except [7] where that amendments had been estimated as (10 – 30) ppm for silicon oil. We hope that the functional dependence of the oil density from the amount of dissolved air and oil compressibility can be investigated using LIOM in near future. It will permit to apply corrections and thus to reduce the density uncertainty up to about (10 – 20) ppm. But the present day we reckon that the relative density uncertainty of 100 ppm is a reliable and sufficient estimation.

3.2. Capillary uncertainty

The capillary uncertainty of pressure measurement is determined by possible fluctuations of the meniscus curvature radii rather than by their values themselves. We evaluated the rate of these fluctuations by means of direct measurements of the curvature radius using a Michelson interferometer [9]. For this purpose, a manometer tube was inserted into one arm of the interferometer, while a flat mirror was placed into the other one. The interferometer was lit by a parallel He-Ne laser beam. The interference pattern localized near the oil surface in a float, which geometry was similar to Newton rings, was recorded by means of a digital video camera with a PC. As a result of processing the sampling of ten shots taken with different positions of the meniscus, the average value of the meniscus curvature radius was $R = 1.40 \text{ m}$ with the dispersion $\delta R = 0.04 \text{ m}$. And thus following estimate was obtained for the capillary uncertainty component of pressure measurement:

$$\delta P = \frac{2\gamma}{R^2} \cdot \delta R = 0,001 \text{ Pa}$$

where $\gamma$ is the surface tension of oil.

A relatively small value of the meniscus curvature fluctuations is probably explained by the fact that the floats isolate the meniscus from the manometer tubes, which results in the contact angle fluctuations staying insignificant during the float displacement.

Results of this research show, that there is no need to increase the tube diameters up to more than 40 mm for reducing the capillary uncertainty, as it has been done before usually. So, the device can be made compact enough to reduce mechanical and temperature instabilities of the interferometer.

3.3. Temperature instability and zero-drift.
To diminish temperature instability the manometer tubes are sunk into water bath. The mercury thermometer with the resolution 0.1º C is used to measure the temperature of the water. The uniformity of the temperature is of great importance because it determines the drift of zero point. The special test in which the pressure didn’t alter showed that it was about 1-1.5 $\lambda$ per hour. That is well
enough because the mean time of the measurement is about 1 – 3 minutes. Another experiment in which the measured pressure was returned to zero gave the similar results.

3.4. Total uncertainty
Today the total uncertainty of the measured pressure \( p \) is estimated to be \((1.0 + 0.01p/\text{Pa}) \times 10^{-2} \text{ Pa}\) in the range 1-1000 Pa. Some planned improvements and further investigations will permit to decrease this value in nearest future.

4. Conclusion
The LIOM is being tested now and after some improvements and further investigations has to be a national standard of RF for absolute pressure in the range 1 – 1000 Pa. LIOM can be used also for measuring gauge-mode pressures and in flow rate measuring setup for calibration of vacuum flow measures – artificial leaks.

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