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REALIZATION OF NATIONAL ABSOLUTE PRESSURE STANDARD AT LPM

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Abstract: This paper presents absolute pressure calibration system in the range from 25 kPa up to 2 MPa which is being developed in Croatian national pressure laboratory-Laboratory for Process Measurement (LPM) at Faculty of Mechanical Engineering and Naval Architecture (FSB) in Zagreb.
Design of the system, theoretical basis, effective area determination methods and the model for estimation of absolute pressure measurement uncertainty are described.

Keywords: absolute pressure mode, piston gauges, calibration.

1. INTRODUCTION

LPM is responsible for the realization, establishment, maintenance and dissemination of the national temperature and pressure standards. Extensive research and development is being performed in the field of pressure metrology resulting in establishment of absolute pressure calibration system which broadens the scope of existing national pressure calibration services.

The need for development of absolute pressure standard arises primarily from applications where sub-atmospheric pressure instruments, such as in aircraft altimeters or barometers must be calibrated. Calibration of gauges and transducers that are used to measure absolute pressure at the lowest level of uncertainty are typically performed using either manometers or piston gauges [1].

Gas-operated piston gauges are becoming more common for absolute pressure measurement because they have several advantages over mercury manometers. They can measure higher pressures and they have much lower thermal expansion coefficient [2].

For this reasons, traceable gas operated piston gauge calibration standard in absolute pressure mode is being developed in LPM.

2. CALIBRATION SYSTEM

2.1. Theory

Absolute pressure is defined as the pressure measured relative to a perfect vacuum (zero hydrostatic pressure). Also, because zero absolute pressure is impossible to achieve it is much harder to measure and calibrate absolute pressure sensors.

Gauge hydrostatic pressure is the value of the “absolute” pressure less or above the ambient “absolute” hydrostatic pressure.

The essential element of the LPM’s absolute pressure calibration system is a piston/cylinder (P/C) assembly. Accurately calibrated weight masses, *M*, are loaded on the vertically positioned piston having effective area *Ae*. The pressure to be measured is applied to the base of the piston creating an upward force. The upward force, *F*, is balanced by the downward weight of loaded masses submitted to the local gravity, g. When the rotating piston is freely floating the gauge pressure p_g in “(1)”is generated:

$$p_g = \frac{F}{A_e} = \frac{M \cdot g}{A_e} \tag{1}$$

The weights are normally surrounded by air at atmospheric pressure and P/C unit operates in gauge mode. The absolute mode, p_a, can be achieved with evacuated bell jar over the P/C unit:

$$p_a = p_g + p_r \tag{2}$$

where, p_r, is the residual pressure in the bell jar.

The performance of the absolute P/C assembly is dependent upon a lubricating film of gas molecules between the piston and cylinder. Calibration in absolute mode is often easier if the residual pressure is not lower than 0,1 Pa. This ensures that there is enough free gas molecules present to provide sufficient lubrication around the piston. When very low residual pressure is achieved, the film of gas molecules may begin to break down. This will cause metal-to metal contact between piston and cylinder, which is undesirable and will affect the performance of the piston.

2.2 Design Features

A commercial gas-operated P/C assembly manufactured by Pressurements with a diameter of 10 mm is used in LPM’s standard for absolute pressure. It can generate pressures from 25 kPa up to 2 MPa. Pressure transmitting medium is nitrogen of high purity.

Bell jar that makes an airtight seal with the base of the gauge is placed over the masses *M*, as shown schematically in Figure 1. A vacuum port is placed in the base so that region under the bell jar can be evacuated using a rotary vane vacuum pump manufactured by Leybold.

Absolute vacuum or zero pressure is only a theoretical state and is impossible to achieve. The residual pressure, p_r, in the evacuated volume adds directly to the pressure generated by the piston gauge to determine the absolute pressure. If this residual pressure in the bell jar is not measured large errors might be introduced into the absolute pressure measurement. To accomplish this Pirani Gauge Head and indicator, fully calibrated as a par, are used.

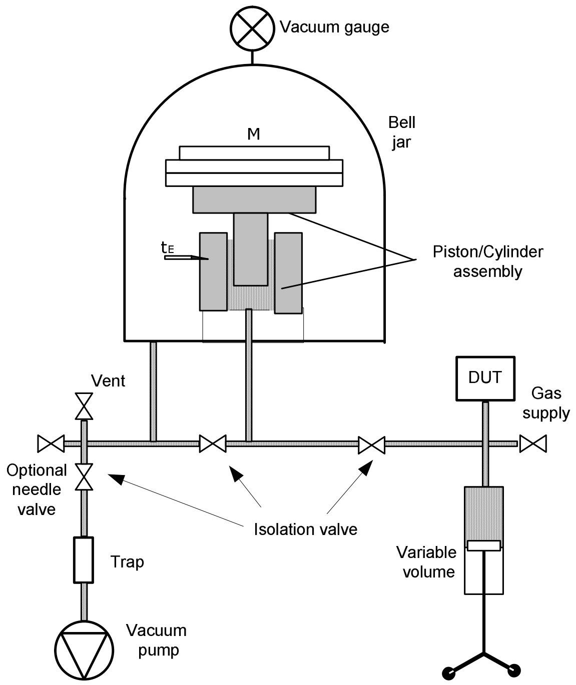

Fig. 1. System configuration

Calibration system basic data are given in Table I

Table I. Basic data for LPM's absolute pressure calibration system.

Standard P/C unit	
Type of standard pressure balance / Manufacturer	Simple / Pressurements U544
Effective area of standard instrument	$(0,805957 \pm 0,000039) \cdot 10^{-4}$ m^2
Volume for buoyancy correction	-0,4 cm^3
Piston/Cylinder material	Steel/Steel
Piston/Cylinder Thermal expansion coefficient	$(16,5 \pm 2,0) \cdot 10^{-6}$ K^{-1}
Vacuum gauge	
Thermal conductivity type:	Pirani- TM22 Leybold Vakuum GmbH (Transmitter TR 211)

To perform fine pressure adjustments in the system a variable volume pressure controller is used. All of the lines in the vacuum system are kept as short as possible for maximum pumping speed and minimum response time of the bell jar pressure measurement system.

System is equipped with a 16 kg mass set of 16 nonmagnetic stainless steel weights. Each disc type weight has a central hole for loading and unloading onto the basic weight placed on top of the piston.

2.3. Determination of effective area

The derivation of effective area of piston cylinder unit represents the largest uncertainty contribution to pressure measurements. Although the LPM P/C assembly was purchased with manufacturer calibration certificate (Table 1), effective area has been measured twice after.

In first calibration, results were obtained by cross-float comparison with other standard P/C unit.

Calibration with lowest uncertainty was performed in German national pressure laboratory – PTB (Physikalisch Technishe Bundesanstalt). Results are shown in Table II. Effective area was obtained with an uncertainty of 50 ppm.

In second case effective area was obtained in LPM from dimensional measurements. Dimensional measurements were performed in Croatian National Laboratory for Length at Faculty of Mechanical Engineering and Naval Architecture. In this case the pressure is directly represented as the ratio of the SI units.

Measurements included the determination of three pairs of orthogonal diameters in three horizontal planes. Measurements were performed with standard contact probe equipment JOINT DMS 680 with uncertainties of 0,25 µm in piston and 0,4 µm in cylinder measurement.

The effective area was simply calculated as the average of all the dimensional data to determine the ''neutral surface'' as an average of the piston $\overline{D_k}$ and cylinder $\overline{D_c}$ radius.

$$A_0 = \frac{\pi}{8}\left(\overline{D_k}^2 + \overline{D_c}^2\right) \tag{3}$$

The uncertainty for the effective area $u(A_0)$ depends on the uncertainty of the diametrical measurements of piston $u(D_k)$ and cylinder $u(D_c)$ and the standard deviations of the mean diameters.

Since the main contribution to the diameter uncertainty is of a systematic nature, the piston and cylinder diameter uncertainties are considered as correlated with correlation factor $\rho(D_k,D_c)=1$.

$$u(A_0) = \frac{\pi}{4}\left[\begin{array}{l}\left(u(D_k)\cdot\overline{D_K}\right)^2 + \left(u(D_c)\cdot\overline{D_c}\right)^2 \\ +2\times u(D_k)\cdot\overline{D_K}\cdot u(D_c)\cdot\overline{D_c}\cdot\rho(D_K,D_c)\end{array}\right]^{1/2} \tag{4}$$

Table II. Effective area calibration results

P/C U544	Effective area A_0 (mm^2)	Measurement Uncertainty u_{A0} (mm^2)
Calibration 1 (Manufacturer)	80,5937	0,0064
Calibration 2 (PTB)	80,5957	0,0039
Calibration 3 (LPM)	80,5951	0,0052

All uncertainties reported in Table II are 99% confidence limits.

2.4. Determination of effective pressure

Taking into account all influencing quantities a gas-operated absolute pressure balance generates pressure p_a at the reference level of the gauge given by:

$$p_a = \frac{\sum_i m_i g \left(1 - \frac{\rho_a}{\rho_{mi}}\right)}{A_0 \cdot (1 + \lambda \cdot p) \cdot \left[1 + \left(\alpha_p + \alpha_c\right) \cdot (t - 20)\right]} + p_r \qquad (5)$$

where :

- p_a is the absolute pressure measured at the bottom of the piston
- m_i is the individual mass value of each weight applied on the piston, including all floating elements
- g is the local gravity
- ρ_a is the density of surrounding air
- ρ_{mi} is the density of each weight
- α_p is the linear thermal expansion coefficient of the piston
- α_c is the linear thermal expansion coefficient of the cylinder
- t is the measured temperature of the piston-cylinder assembly during its use
- A_0 is the effective area at null pressure [3]
- λ is the pressure distortion coefficient
- p_r is the pressure in the region above the pressure balance

Since the air density in the evacuated bell jar is extremely small, the buoyancy term in Equation 3 can almost always be neglected, however, true mass values were used. Pressure distortion coefficient is assumed to be zero.

3. MEASUREMENT UNCERTAINTIES

As always, the way the measurement uncertainties are estimated is dependent on the type of the device under test (DUT). In this case the calibration of absolute pressure transducer is considered. In such case uncertainty budget can be estimated in the following way, [4,5]:

Sources of uncertainty are divided in three groups: pressure standard (P/C unit), calibration method and DUT.

Combined standard uncertainty of calibration result, u, can be calculated according to the equation (6):

$$u^2 = u_{PC}{}^2 + u_{Corr}{}^2 + u_{cm}{}^2 + u_r{}^2 + u_{f_0}{}^2 + u_b{}^2 + u_h{}^2 \qquad (6)$$

where:

u_{PC}-P/C unit uncertainty taken from calibration report
u_{Corr}-P/C unit uncertainties under conditions of calibration
u_{cm} -calibration method uncertainty
u_r -resolution uncertainty caused by DUT
u_{fo} -zero deviation uncertainty (DUT)
u_b -repeatability uncertainty (DUT)
u_h -hysteresis uncertainty (DUT)

Uncertainties u_{PC} and u_{Corr} pertain to pressure standard.

P/C unit uncertainties under conditions of calibration, u_{Corr}, are calculated as Type B, from partial derivatives (sensitivities) of eq.(5) taking into account following quantities:

- uncertainty of the masses, u_M,
- uncertainty of the P/C effective area, u_{Ae} which comes from the calibration certificate
- uncertainty due to temperature of the standard u_t, which comes from calibration of thermometer
- uncertainties of thermal expansion coefficients of standard piston and cylinder, $u_{2\alpha}$
- uncertainty due to density of the load, $u_{\rho m}$
- uncertainty due to air buoyancy, $u_{\rho a}$
- uncertainty due to head correction, $u_{\Delta h}$

Combined standard uncertainties (Type B) of of the P/C assembly, $u_{P/C}$, which takes into account uncertainties of the effective area u_{Ae}, masses u_M, temperature u_t, temperature coefficients $u_{2\alpha}$, and densities of the masses $u_{\rho m}$, is calculated as:

$$u_{P/C} = \sqrt{\left(\frac{\partial p_a}{\partial A_e} \cdot u_{Ae}\right)^2 + \left(\frac{\partial p_a}{\partial M} \cdot u_M\right)^2 + \left(\frac{\partial p_a}{\partial t} \cdot u_t\right)^2 + \left(\frac{\partial p_a}{\partial 2\alpha} \cdot u_{2\alpha}\right)^2 + \left(\frac{\partial p_a}{\partial \rho_m} \cdot u_{\rho m}\right)^2} \qquad (7)$$

Uncertainty u_{cm} generally pertains to calibration method and can include: static pressure differences (differences in height of reference levels of standard and DUT), in transducer calibration possible influence of amplifiers, frequency meters, voltmeters (not applicable in this case), etc.

Uncertainties u_r, u_{fo}, u_b and u_h pertain to DUT and they are all evaluated the same way, i.e. assuming rectangular distribution of their limiting values.

Most of above mentioned uncertainties are taken from latest calibration report except uncertainty values for thermal expansion coefficient and densities of the loads which are found in literature.

Uncertainties of the masses are calculated as sum of the standard uncertainties of the individual weights because correlation coefficient 1 is assumed:

$$u_M = \sum_i u_{m_i} \quad (8)$$

After all the uncertainty components have been individually evaluated and converted into standard uncertainties (single standard deviations) they are combined by root-sum-of-squares summation.

Combined standard absolute pressure Type B uncertainty, u_{pa}, is calculated according to the equation (8):

$$u_{pa}{}^2 = u_{P/C}{}^2 + u_{pr}{}^2 \quad (9)$$

where,

$u_{P/C}$ -is P/C unit uncertainty

u_{pr}: -is uncertainty of residual pressure measurement

4. CONCLUSION

The demand for absolute pressure calibration in Croatia has spurred the development of calibration system and calibration methodology in the absolute pressure range from 25 kPa up to 2 MPa Absolute pressure piston gauge standard has been established in LPM. In order to build up and maintain confidence in the metrological characteristics and to provide international traceability, P/C effective area was calibrated twice and traceability to PTB and Croatian Length Laboratory was achieved.

System design and theoretical basis are given. Main parameters influencing the effective pressure and the model for estimation of measurement uncertainty are described. Measurement uncertainty of described system is expected to be better than 60 ppm.

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