New calibration procedure for differential pressure using twin pressure balances for flowrate measurement

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Abstract. Reliable pressure measurements are essential in all activities of society and industry. Indeed, the concern with traceability has notably improved and has received considerable interest due to the intensification of international trade, the need for environmental issues, safety and health requirements, for example in medical instruments, as well as devices for measuring the flow of Fluids Based on the pressure change. Differential pressure sensors are widely used in fluid flow processes, such as for monitoring the flow conditions and to determine flowrate or fluid velocity (example are the Pitot tube, Venturi, orifice plate etc.). This study focused on the precise generation of differential pressures in the range of 500 kPa to 20 MPa using gas-operated twin pressure balances. The metrological characteristics of a differential pressure manometer were evaluated.

1. Introduction

Pressure measurements play an important role in industrial processes. There are several applications of pressure quantity; for example, in the petroleum, petrochemical, meteorological, aerospace, aviation, industries etc. The reliability of these measurements is associated with trade, quality, health, safety, etc.

Pressure measurement instruments can be classified into two main groups: fundamental and relative. The fundamental instruments measure pressure from the definition of quantity. In this group are included the liquid column manometer and the pressure balance.

The pressure balance that can measure absolute pressure, differential pressure, gauge pressure and vacuum. [8], is a fundamental group meter widely used as reference standard in the measurement of the pressure magnitude. It consists basically of a piston-cylinder assembly, a set of masses and a watertight system where the fluid is contained which will generate the pressure to be measured which acts at the base of the piston. Figure 1.

The magnitude of the pressure balance measured from the balance between the force resulting from the pressure of a fluid (gas or liquid) acting at the base of the piston with the force coming from the
masses acting at the top of the piston. The equation of pressure measurement by a pressure balance is defined by equation 1

\[ p = \frac{m_p(1 - \frac{\rho_a}{\rho_{mp}}) + \Sigma m(1 - \frac{\rho_a}{\rho_{mp}})g + \sigma C}{A_{0,2d}[1+(\alpha_c + \alpha_p)\cdot(\theta - 20)](1 + \lambda p_n)} \pm \rho_{fluid}g\Delta h \] (1)

where:
- \( p \) is the measured pressure;
- \( m_p \) is the mass of the piston;
- \( \rho_a \) is the specific mass of the air;
- \( \rho_{mp} \) is the specific mass of the piston material;
- \( \Sigma m \) is the sum of the remaining masses acting at the top of the piston;
- \( \rho_m \) is the specific mass of the material of the remaining masses;
- \( g \) is the acceleration due to local gravity;
- \( \sigma \) is the surface tension of the fluid;
- \( C \) is the length of the circumference of the piston;
- \( A_{0,20} \) is the area of the cylinder piston set;
- \( \alpha_c + \alpha_p \) are the coefficient of linear thermal expansion of the piston-cylinder assembly;
- \( \theta \) is the piston temperature at the time of measurement;
- \( \lambda \) is the coefficient of deformation of the piston-cylinder assembly;
- \( p_n \) is the nominal pressure of the measurement;
- \( \rho_{fluid} \) is the density of the working fluid;
- \( \Delta h \) is the difference between the base of the piston and the point where the pressure is measured; In equation 1, the value of \( \Delta h \) is negative when the piston base of the pressure balance is below the pressure measurement point, and positive when the base is above the pressure measurement point.

The relative instruments measure the pressure in function of a physical property or a physical phenomenon. In this group are included manometers, vacuometers, manovacuometers, digital piston manometers, pressure transducers / transmitters, etc.

Differential pressure sensors are widely used in fluid flow processes, such as for monitoring the flow conditions and to determine flowrate or fluid velocity (example are the Pitot tube, Venturi, orifice plate etc.). The typical dependency of these meters on \( \Delta p \) is given by a square relationship, thus, the more large an expected measurement range of such meters, the more large a necessary range of a \( \Delta p \) sensor. Otherwise, while the flowrate range decreases, the respective uncertainty increases due to the difficulty of measuring accurately the low level of its related differential pressure. In order to minimize this impact, it could be used more than one instrument for differential pressure measurement, of for each range. However, independent on the range, the calibration of the differential pressure sensor is fundamental for the reliability of flow measurements.
2. Objectives

The objective is to propose a new methodology to be applied to differential pressure measurement using two reference pressure balances.

3. Methodology

3.1. Calibration Procedure

In calibration care must be taken regarding the instrument in calibration such as: cleaning; being it digital must be connected before to the electrical network for a period of 30 minutes and in which fluid it should be calibrated. The standards used must have at least one accuracy class four times better than the instrument to be calibrated. Before starting calibration with the instrument connected to both standards, its maximum pressure must be applied for 10 minutes to check for system leakage. The meter shall be calibrated in its working position (vertical or horizontal) at ten points at increasing and decreasing pressure and the measurements shall be recorded on the calibration worksheet.

3.2. Differential Reference Pressure Calculation

When two pressure balances are used in calibration the reference differential pressure is defined by equation 2.

\[ \Delta P_{ref} = P_{ref1} - P_{ref2} = \]

\[ \frac{A_{10,20}}{A_{20,20}} \left[ \left( 1 + (\alpha_{c1} + \alpha_{p1}) \cdot (t_1 - 20) \right) \cdot (1 + \lambda_{1} \rho_{n}) \right] \cdot \frac{M_{p1} \cdot \left( 1 - \frac{\rho a}{\rho_{M1}} \right) + \sum M_1 \left( 1 - \frac{\rho a}{\rho_{M1}} \right) \cdot g + \sigma C_1}{g \cdot \Delta h} \]  

\[ \frac{A_{10,20}}{A_{20,20}} \left[ \left( 1 + (\alpha_{c2} + \alpha_{p2}) \cdot (t_2 - 20) \right) \cdot (1 + \lambda_{2} \rho_{n}) \right] \cdot \frac{M_{p2} \cdot \left( 1 - \frac{\rho a}{\rho_{M2}} \right) + \sum M_2 \left( 1 - \frac{\rho a}{\rho_{M2}} \right) \cdot g + \sigma C_2}{g \cdot \Delta h} \]  

where all the variables of the equation 2 have already been described in the previous item.

3.3. Measurement Uncertainty

The uncertainty of measurement in the calibration of a pressure balance is estimated according to "JCGM 100: 2008 - GUM 1995 with minor corrections - Evaluation of measurement data - Guide to the expression of uncertainty in measurement - First edition September 2008 ".
The measured in a calibration is the value of the quantity that defines the error of the instrument. Thus in the case of calibration of the differential pressure manometer the error is defined by the expression 3.

\[ e(p) = \Delta P_i - \Delta P_{ref} \] (3)

At where: \( e(p) \) is the error of the instrument; \( \Delta P_i \) is the magnitude value indicated by the instrument and \( \Delta P_{ref} \) is the magnitude value measured by the standard.

Thus, considering equations 2 and 3, show the cause-effect diagram of the calibration performed by two twin pressure balance.

![Diagram cause-effect of the calibration](image)

**Figure 3. Diagram cause-effect of the calibration**

### 4. Results and Discussion

#### 4.1. Errors

Table 1 shows the instrument errors according to equations 3.

| \( \Delta P_i \) | Error   |
|-----------------|---------|
| bar             |         |
| 0,00            | 0,00    | 0,01 | 0,01 | 0,01 |
| 1,00            | -0,01   | -0,01| -0,04| -0,01|
| 2,00            | -0,05   | -0,04| -0,04| -0,04|
| 3,00            | -0,06   | -0,11| -0,11| -0,11|
| 4,00            | -0,09   | -0,13| -0,14| -0,13|
| 5,00            | -0,12   | -0,16| -0,13| -0,16|
| 6,00            | -0,15   | -0,20| -0,15| -0,20|
| 7,00            | -0,28   | -0,24| -0,18| -0,24|
| 8,00            | -0,28   | -0,24| -0,16| -0,24|
| 9,00            | -0,33   | -0,36| -0,29| -0,36|
| 10,00           | -0,37   | -0,39| -0,27| -0,39|
The graph of figure 4 shows that errors are contained in the intervals defined by their systematic errors plus or minus half resolution of the calibrated instrument (±0.1 bar).

![Errors as function of pressure](image)

**Figure 4** Instrument error curve -

This step is very important because it can be used as a tool for the evaluation of calibration quality control. A calibration is under control when all punctual instrument errors are contained within the range defined by punctual systematic errors plus or minus half the resolution of the calibrated instrument.

4.2. Hysteresis, repeatability and linearity

Table 2 presents the metrological characteristics of the manometer: maximum error, hysteresis, repeatability, linearity and the calibration curve of the instrument. The percentage values shown are in relation to the amplitude of the measuring range of the instrument.

| Maximum error (%) | 2.3 |
|-------------------|-----|
| Hysteresis (%)    | 0.7 |
| Repeatability (%) | 0.7 |
| Linearity (%)     | 0.6 |
| Calibration curve | $\Delta P_{ref} = 1.0359 \Delta P_i - 0.0212$ |

4.3. Measurement Uncertainty

The graphs of Figures 5A and 5B show, respectively, the budget of uncertainties in the lower and upper limits of the manometer measurement range. It is observed that in the two limits the uncertainty that most impacts is that coming from the resolution of the instrument.
Table 3 presents the expanded uncertainty (U) of the manometer with the respective coverage factors for the 95% confidence level.

Table 3 Expanded uncertainty

| Pressure (psi) | Coverage factor (k) | U (bar) |
|---------------|---------------------|--------|
| 0,00          | 2,00                | 0,12   |
| 1,00          | 2,00                | 0,12   |
| 2,00          | 2,00                | 0,12   |
| 3,00          | 2,00                | 0,12   |
| 4,00          | 2,00                | 0,12   |
| 5,00          | 2,00                | 0,12   |
| 6,00          | 2,00                | 0,12   |
| 7,00          | 2,01                | 0,13   |
| 8,00          | 2,02                | 0,13   |
| 9,00          | 2,00                | 0,12   |
| 10,00         | 2,03                | 0,14   |

5. Conclusion

A new methodology to be applied to differential pressure measurement using two reference pressure balances is proposed. Manometer errors are contained within the intervals defined by point systematic errors ±0,1 bar. The source of uncertainty that most impacts the calibration is that coming from the resolution of the instrument. The calibration uncertainty varied from 0.12 bar to 0.14 bar.

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