

# A NEW METHOD TO CALIBRATE PRESSURE GAUGES FOR PNEUMATIC APPLICATIONS

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## Abstract

*Pressure gauges are devices for measuring and monitoring pressure in fluid lines such as air, steam, oil and water. These devices generally support pressure in a diaphragm instrumented strain gauges. The pressure is converted to analog electrical signals, which are then processed and converted into digital signals for data acquisition. These pressure gauges are widely used in the mechanical, chemical, petrochemical, aerospace, agricultural, medical industries, etc. The calibration process follows routines described in other procedures, which allows for verification of compliance of the results. However, the process is not always automatic and may add uncertain components and spend a significant time. This work aims to develop a methodology for calibrating pressure gauges, based on the best practices, and a computer program capable of managing the automated calibration process. The program will be developed on a LabView platform with the implementation of statistical tools to assist in the analysis of calibration device. The pressure gauges used in this work are capable of measuring 200 psi (~ 13.8 bar) and are used in conventional compressed air lines. The calibrations were performed with a maximum pressure of 6 bar. The method showed adequate results and allowed for the calibration of gauges in significantly less time than the conventional methods. In addition, the system features developed software which can be adapted to any kind of calibration of pressure gauges based on strain gauges. The method met the objectives, allowing for quick and reliable calibration of pressure gauges. (Mechatronics, automation, control and metrology)*

**Keywords:** calibration, pressure transducer

## 1. INTRODUCTION

The objective of this work is to develop a new automated methodology for calibration of pressure gauges. During this research, a brief review will be conducted covering the basics foundations of pressure measurement, pressure gauge, calibration methods, and statistical evaluation. The methodology should be easy to understand, feasible, allow for clear analysis of the results, and also have advantages with respect to calibration time, besides the program's ease of use.

Calibration is a method widely used by research laboratories and companies looking for quality and reliability. Basically, it means to compare the instrument under analysis to a higher standard, i.e. with lower uncertainty. These labs, in turn, develop their own procedures to standardize and control the calibration. Among the numerous works related to calibration performed by certified laboratories are the calibration guides developed by INMETRO - National Institute of Metrology, Standardization and Industrial Quality (INMETRO, 2010), and the one developed by EURAMET - European Association of National Metrology Institutes (EURAMET, 2007). Among the works carried out by researchers investigating this issue are those of Bao et al. (2003), Wuest et al. (2007), Kojima, Saitou and Kobata (2007) and Ripper et al. (2009), each one with specific approaches, demonstrating the feasibility of the employment of new methods for calibration.

In order to achieve the objective proposed in this paper, a previous study of different forms of calibration of pressure gauges was developed to define the optimal method for pressure calibration. For this, we used two pressure gauges with a capacity of 200 psi (13.8 bar) connected to a compressed air network of 6 bar regulated through a manometer. The pressures were determined by software built in LabVIEW 8.2 platform. This software and the setup enable the pressures to be measured in two different gauges simultaneously. By varying the pressure in the line where the two gauges mentioned previously were connected. We found the adjustment of the gauge to be calibrated, provided the other gauge is calibrated. Using this methodology, we determined the fitting curve for the pressure gauge, allowing its calibration.

## 2. BASICS FOUNDATIONS OF CALIBRATION

Calibration requires the knowledge about the parameter under evaluation, the forms to measure the parameters, and the main methods to treat the results. This topic describes each one of those, focusing on the problem of measuring the pressure.

### 2.1 Pressure Measurement

Pressure measurement can be performed in two ways, by reference instruments (often mechanical) or pressure gauges, being the medium in which it works and its required precision the determinant factors to choose the type of instrument utilized (Doebelin, 2004).

The pressure gauges act like sensors. The second includes the first. Sensor element (elastic) absorbs the deformations, which is transformed in measurable signals by the gauge (Figliola and Beasley, 2006).

The pressure gauges based on strain-gages are widely employed due to their set of unique features, having high accuracy and stability, which make them known like field gauges. Such advantages are due to:

- Small size and mass, an important factor when it is necessary to reduce inertia effects
- The strain-gage is linked to basic elastic structure, ensuring high linearity and large range of deformation
- The low effect of temperature in the equipment
- The output of the circuit is the variation of its resistance

The elastic diaphragm is a thin plate of metal (sensor element), in most cases of stainless steel. This membrane is the most critical mechanical component, since the device is responsible to transmit the deformation to the gauge. It is important to emphasize that deformation of the diaphragm should vary linearly with the change in resistance, as any conventional gauge (Window, 1992).

The excitations provided from deformation of sensor element change the resistance in two (or four) arms of Wheatstone bridge, which correspond to gauge element of these strain-gages. This excitation is transmitted to the system of signal processing through the electrical connector.

Another feature of this type of gauge is the presence of a stop bar, which is activated when the pressure exceeds the limit of the gauge (Norton, 1969).

## 2.2 Calibration of Pressure Measurement Valves

The calibration process aims to establish the variables that describe the global function of transference of the equipments (Fraden, 2003). So, if the mathematical model that describes this function is linear, the calibration consists of finding the slope and the intercept of the straight line in the graph.

According to Doebelin (2004), an accurate pressure measurement standard ensures the calibration of instruments of lower accuracy. Such standards are defined in accordance with the pressure range.

One type of calibration is the static calibration, which is performed by direct comparison of measurements obtained by the equipment to be calibrated with the values provided by the instrument of more accuracy (reference instrument), or a standard gauge certificated by a laboratory (Figliola and Beasley, 2006).

The procedure of calibration consist of applying known pressure values in the gauge chamber, exposing the gauges simultaneously to the same level of pressure, in order to plot a graph that describes the relation between the pressures of standard gauge and the calibrated gauge. The pair of values is taken after the stabilization of the pressure. The graph obtained plots the calibration curve.

As the curve of static calibration correlates static input and output variables, this curve is valuable for the development of functional relation between the variables. The correlation is obtained through physical reasoning and by applying techniques of curve fitting in the calibration graph.

The term 'static' used in this kind of calibration is because the variables involved in the process are constant; they do not vary with time. So, only the input and output values are considered important (Figliola and Beasley, 2006).

However, there are also dynamic calibrations, for which the variables change with time (or space). In this type of calibration, the value is the rise time and frequency response of pressure gauges. The time dependence of these variables is both in the magnitude and in the frequency (Figliola and Beasley, 2006). These calibrations use a sinusoidal signal or step change as input variables. An electric switching valve is used to generate such step change. Therefore, dynamic calibration correlates the dynamic behavior of known input and output measurement system.

No matter the kind of calibration, this proceeding can be automated in order to improve its quality, organization and accuracy, providing a more detailed report.

To automate a calibration, it is required a good understanding of the action of each variable in the process and their interrelationship (Fluke, 1994). Although this process is laborious, it guarantees more consistent measurements, increasing productivity. It also offers automatic documentation and reduction of the procedure cost.

## 2.3. Curve Quality and Fitting

According to Vuolo (2000) and Griffiths (2009), to determine the equation of the curve fitting  $Y$ , that matches to the static calibration of the equipment, it is necessary find the parameters  $a$  and  $b$ , Equations 2 and 3, respectively.

$$Y = ax + b \tag{1}$$

$$a = \frac{1}{\Delta} (S_0 \cdot S_{XY} - S_X \cdot S_Y) \tag{2}$$



## 2.4. Propagation and Transfer of Uncertainty

According Vuolo (2000) and INMETRO (2003), assuming a magnitude  $w$  in function of other magnitudes  $x$ ,  $y$  and  $z$ , represented by  $w = w(x, y, z)$ . The uncertainties standards are  $\sigma_x$ ,  $\sigma_y$  and  $\sigma_z$ , respectively. If the errors are independent between them, the uncertainty standard in  $w$  is

$$\sigma_w^2 = \left(\frac{\partial w}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial w}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial w}{\partial z}\right)^2 \sigma_z^2 \quad (9)$$

Suppose we have a magnitude  $y$  measure in function of variable  $x$  which is independent ( $y = f(x)$ ). Therefore,  $x$  and  $y$  should be show in chart with uncertainty bars. The uncertainty of the variable  $x$  is transfer to magnitude  $y$ , so we will have an increase in uncertainty  $y$  resulting in a variance  $\sigma_y^2$ , Equation 10.

$$\sigma_y^2 = \sigma_{y0}^2 + \left(\frac{dy}{dx}\right)_0^2 \sigma_x^2 \quad (10)$$

Where  $\sigma_{y0}^2$  is the original variance and  $\left(\frac{dy}{dx}\right)_0^2 \sigma_x^2$  is the variance representing the transfer uncertainty from  $x$  to  $y$  along with a preliminary estimate of the derivative  $\left(\frac{dy}{dx}\right)$ .

## 3. PROCEDURE AND MATERIALS FOR CALIBRATION OF PRESSURE GAUGE

The following text describes the equipment and the software used in the process of automating the calibration process.

### 3.1. Equipment

For the experiment, we used two pressure gauges Sensotec with a maximum capacity of 200 psi (~ 13.8 psi) that are equivalent to the model JTE 708-12 from Honeywell. The pressure control system consists of a proportional and open/close valve used for regulating the inlet pressure of the pressure gauges. Its brands are Mannesmann Rexroth, model DE561 012 062 0, and Micro, respectively. A relay control system Finder 10A 250V (24V DC) and an optical sensor Conexel (250V~) complete the system. The electrical system is powered by a source Fontat 24V 2A (110/220V). These are interrelated and connected to a compressed air line with 6 bar pressure regulated by a pressure manometer Festo.

For signal acquisition and control, we used an acquisition board National Instruments NI PCI 6229 -16 Bit, 250 kS/s, 32 analog inputs with a block of connections. We also used a signal conditioner model CB 68LP and an amplifier Measurement Instruments, Model 2160. Figure 3 shows the complete system used in the experiment.

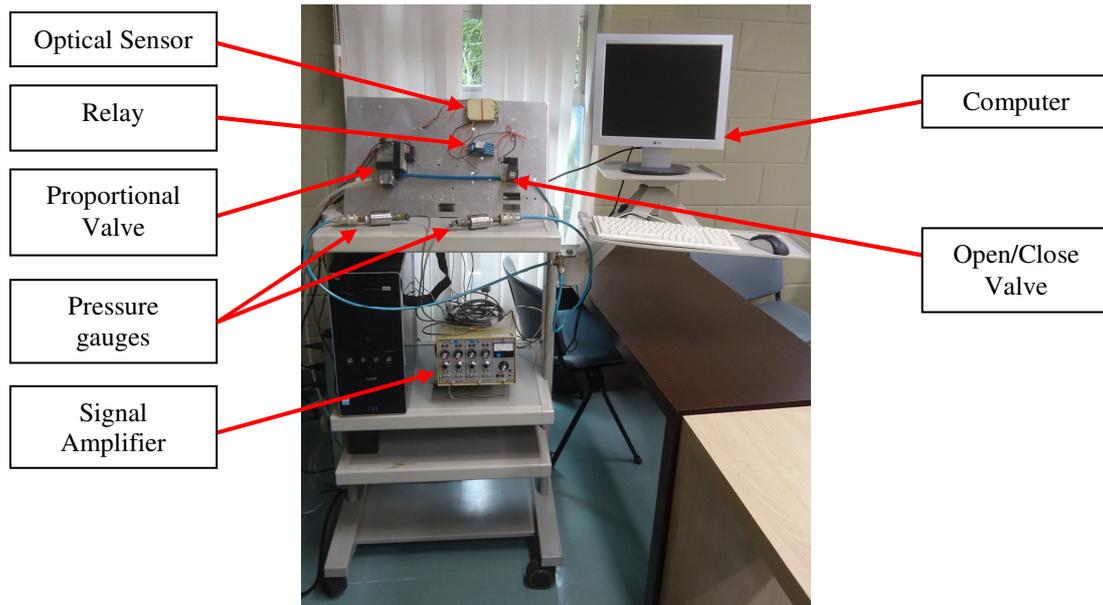


Figure 3. System for monitoring signals and calibrating the pressure gauges.

### 3.2. Program to Analyze the Data and Calibrate the Gauges

The program for the calibration of pressure gauges was developed in LabVIEW 8.2 platform. The front page of the program introduces data of the title, author, institution, release, and date of development of the program.

Figure 4 shows the second page of the program, which presents the drivers of the program for calibration of the pressure gauges. This is used to set the input variables in the program (input voltage (V), output voltage (V), Calibration Factor (mV/V), excitation voltage (V), amplification, and capacity meter (psi). It has a button to control the proportional valve. It also has charts (Pressure Gauge Signal 1 and 2) and indicators (Gauge 1 and 2) to identify the balance and control the voltage signal sent by the valves.

The program controls automatically the opening of the proportional valve, which corresponds to the pressures level. Therefore, it is important to highlight that the number of steps is fixed in twelve levels, being six of rise and six of descent. The increment in each step is a function of the final and initial pressures.

Other characteristic of the program is that it saves and reads automatically the data files generated as “.lvm” (Data Files, Archives of Standard Deviation and Average Pressure in the Standard Gauge), reducing the time and the operations made by the user.

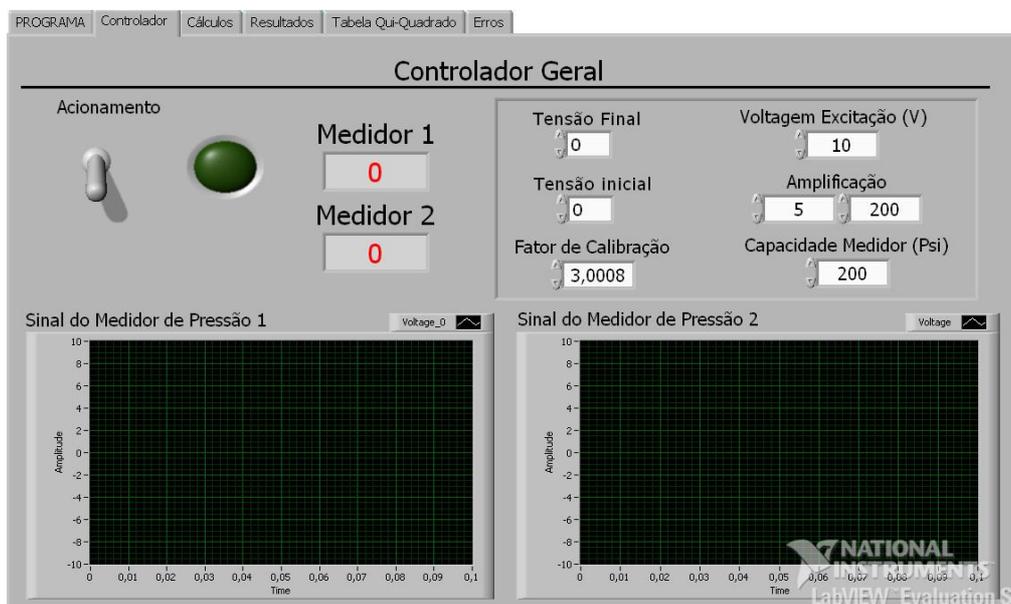


Figure 4 – Second page of the program for calibration of pressure gauges.

Figure 5 shows the third page of the program presents the calculations of the average read voltage on the pressure gauge to be calibrated (Average  $Y_i$  (V)) and the standard uncertainty read voltage ( $\text{Sigma } i$ ). After this, the calculation of  $S_x$ ,  $S_x^2$ ,  $S_{sig}$ ,  $S_y$  and  $S_{xy}$  are needed to determine the adjusted parameters the curve. The sigma x represented the standard deviation that is use to calculate the transfer of uncertainty  $DP_{y+x}$ , being that  $(dy/dx)$  is considered equal to 1.

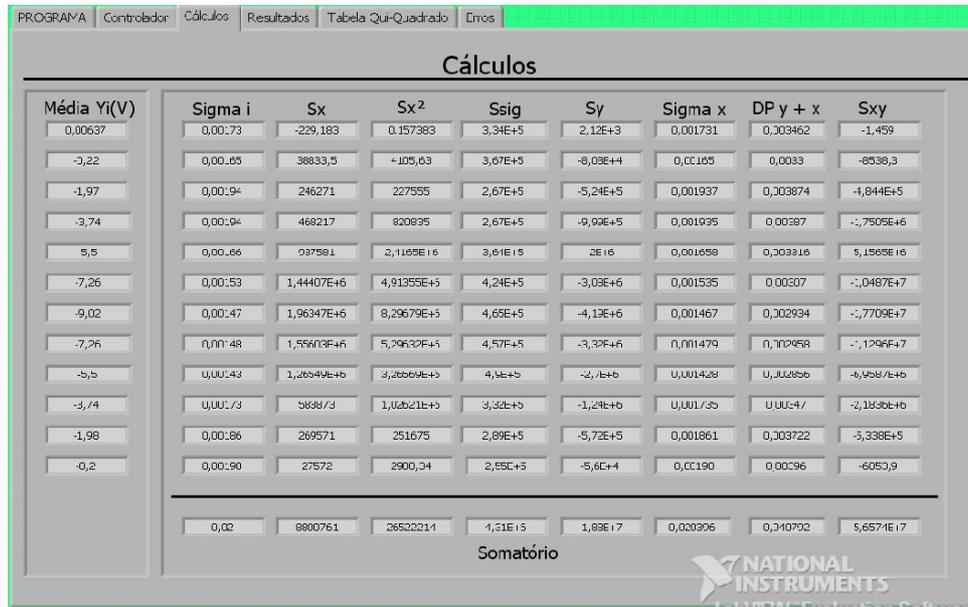


Figure 5 – Third page of the program for calibration of pressure gauges.

Figure 6 presents the calculations of the determinant  $\Delta$ , the determination coefficient  $R^2$  and the parameters  $a$  and  $b$  for the adjusted curve. In the upper right is the graph of Average Read Voltage (V) X Pressure (bar). In the lower region of the page, we show the calculation of the quality of the adjusting using the Least Squares Method and the calculations of Reduced Chi-square. Using the Method of Maximum Likelihood, we need to input the data of the levels and the number of the points that do not cross the adjusted straight line. To use the reduced chi-square, it is necessary to place the  $Q2$  upper and  $Q1$  lower limit, which can be found in the table on the fifth page of a program (similar to the Table 1). For this we need to know the percentage of confidence that can be determined by the area at the right of the critical value available in the table. In the upper central region, we have Read Voltages (V), which was acquired from the standard pressure gauge and at its right, the Pressure (bar) determined by the equation:

$$P = \frac{FSC \times V}{EV \times CF \times A} \tag{11}$$

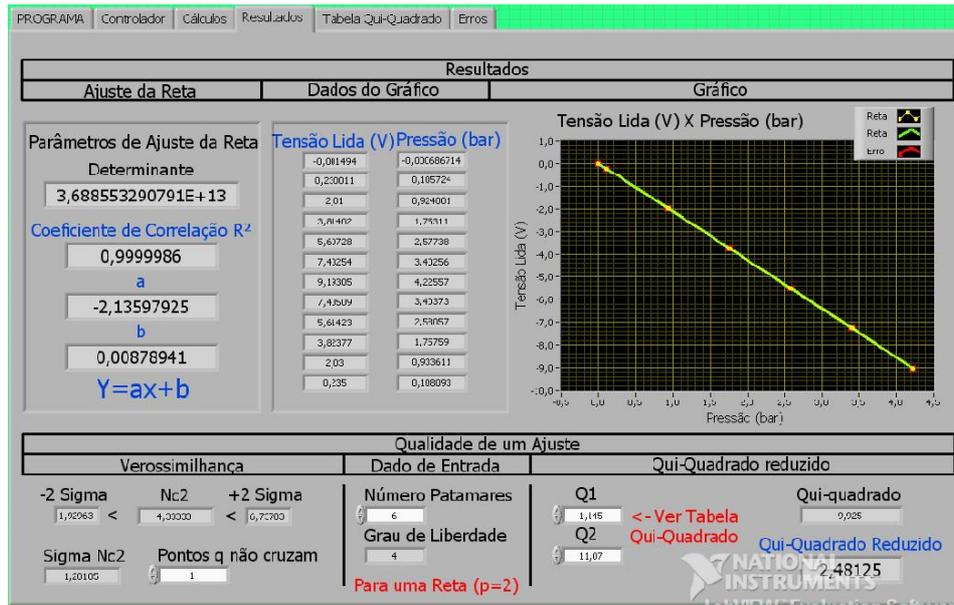


Figure 6. Fourth page of the calibration of pressure gauges program.

In Equation 11,  $P$  is the pressure,  $FSC$  is the total capacity of the pressure gauge,  $V$  is the read voltage,  $EV$  is the excitation voltage,  $CF$  is the calibration factor and  $A$  is the amplification. This formula is used with a previous calibration chart, which came with the transducer.

This calculation is performed automatically by the program, and all the user needs to do is input the data in the Controller and Results page of the program, according to the units in each field. The page called “Errors” in the program shows the errors boxes generated by input or output channel and data of the program. It also shows the identified errors boxes in the program readings, mainly those generated by the acquisition of signals from the pressure gauges.

#### 4. RESULTS AND DISCUSSION

As we can see by the adjusting parameters, the straight line generated by the program is different for each gauge. Table 2 shows the results of the parameters  $a$  and  $b$  from comparison between the pressure gauges 1 and 2 performed by the program. To check the results, we used the Equation 2 and parameters  $a$  and  $b$  extracted from Table 2. The value of  $x$  is the pressure ( $P$ ) found from the pressure gauge to be calibrated, which is given in Equation 12.

$$x = P = K.TL \tag{12}$$

Table 2. Parameters  $a$  and  $b$  from the program for calibration of the pressure gauges.

Parameters	Value
$a$	-2.136
$b$	0.009

$K$  is the calibration factor resulting from the program,  $TL$  is the read voltage from the pressure gauge to be calibrated in volts, and  $Y$  is the average read voltage in volts (Average  $Y_i$  (V)). The last parameter is found for the standard gauge. Thus, the calibration factor  $K$  determined is equal to 0.468. The calibration factor resulting from the calculation is 0.459. This corresponds to an approximate fit with a small difference in one pressure gauge from the other.

To find the average number of uncertainty bars ( $\bar{N}_{cz}$ ) we applied the method of likelihood. We considered the number of points and the curve parameter equal to 6 and 2, respectively. Thus we found the value of  $\bar{N}_{cz}$  equal to 4.33 and  $\sigma_{N_{cz}} = 1.20135 = 1$ . With this, we have only one uncertainty bars crossed the fitted straight line. This corresponds to a fitting curve with bad fit. Thus, it was necessary to use a chi-square method with higher accuracy than the method of likelihood.

To determine the chi-square we also used points numbers and adjusting parameters equal to 6 and 2. The degrees of freedom are equal to 4, so the values of  $Q1$  and  $Q2$  that define the confidence interval of 90% to chi-square corresponds

to 1.145 and 11.070, but the reduced chi-square is equal to 0.1145 and 1.1070, respectively. The reduced chi-square determined by programa is equal to 2.4812. This value is outside the range of acceptable value for chi-square reduced, so the adjustment can be considered good. However, there is a possibility that the uncertainties were overestimated or underestimated. In addition, there is chance that straight line is an inappropriate function to be adjusted. Figure 7 shows the graph of Read Voltage (V) X Pressure (bar).

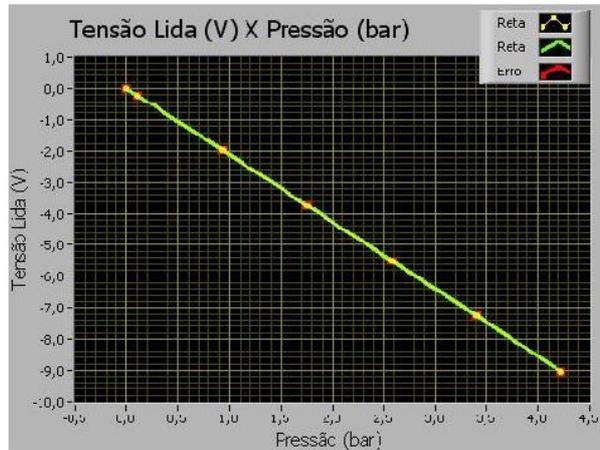


Figure 7. Read Voltage (V) X Pressure (bar) chart from the program of calibration of the pressure gauges.

Figure 7 shows the distribution of points that appears in yellow, the straight line through them generated in green and uncertainty bars in red. The line has the parameters  $a$  and  $b$ . The determination coefficient  $R^2$  obtained when comparing the two pressure gauges is 0.9999986, corresponding to an adjustment of the line in 99.99%. Thus, the fit is considered adequate, because it is above 95%, which is the value of reference.

## 5. CONCLUSIONS

The program developed meets the objectives established by this work, providing a quick and reliable calibration of pressures gauges. This calibration is automated, thus, does not require all laborious operations of fitting curve. Another advantage is that the program allows the measurement of the pressure on two pressures gauges simultaneously and saves such measurements to posterior analyze. Besides, the variation of the pressure levels is automatic, allowing for more precise adjustment.

When comparing the two set of data, we obtained a good fit in both the straight line. The determination coefficients  $R^2$  calculated using the program had value equal to 99.99% for both sets of data.

Using the parameters  $a$  and  $b$  presented by the program we calculate the calibration factor  $K$ , which resulting value is equal to 0.468. The value found for the calibration factor  $K$  calculated using the formula of pressure, Equation 9, is equal to 0.459, which is the value we reported as corrected, once it came from a previous calibration using standard methods. Checking the fitted straight line, we can conclude that the results we got are adequate.

Through the method of likelihood we estimated the value of  $\bar{N}_{CZ}$ , i.e., the average number of uncertainty bars that cross the line, which is equal to 4.33. For this calculation, we considered the number of points and curve parameter equal to 6 and 2, respectively. According with this way of looking the results, the fit is not adequate because only one uncertainty bar crossed the fitted straight line ( $\sigma_{N_{CZ}} = 1.20135 = 1$ ).

Using the chi-square method, the value of chi-square is approximately 9.925 and reduced chi-square is 2.4812. The later is out of the limits:  $Q1$  of 1.145 and  $Q2$  of 11.070 for a confidence interval of 90% and 4 degrees of freedom, determined by Table 1 in Chapter 2. As the value of chi-square is between the range of  $Q1$  and  $Q2$ , we can assume that fitting curve has a good fit.

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