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THE CALIBRATION OF A DIFFERENTIAL PRESSURE TRANSDUCER AT THE OPERATING PRESSURE WITH A PRESSURE AMPLIFIER

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Abstract – The measurement of the differential pressure is widely employed in the petrol industry for determining the flow rate, level, blockage of filters and the oil-water interface. The calibration of the differential pressure transmitters is usually made at atmospheric pressure, since there is little concern about the static pressure influence on the transducer performance. As a main contribution, this paper presents a calibration methodology of differential pressure transmitters. The ranges of the studied static pressure (from 0 to 20000 kPa) and differential pressure (from 40 to 250 kPa) cover Petrobras production and exploration operating conditions. To achieve the results, a pressure amplification device was developed and used at each port of the pressure transmitter. Thus, during the calibration of a pressure transmitter, the pressure differential at the transmitter ports is deduced from the measured value at nearly atmospheric pressure and the amplification factor. The uncertainty of the results was estimated and the methodology was used for the calibration of a pressure transmitter, showing that its calibrating curve varies with the operating pressure.

Keywords : Differential pressure transmitter calibration, Pressure amplifier, Metrology.

1. INTRODUCTION

A differential pressure transmitter is widely used for measuring flow rate with orifice plates, nozzles and venturis in the Petroleum industry.

The calibration of the differential pressure transmitter is made by many laboratories at nearly atmospheric pressure, supposing that its performance curve does not change with the operating static pressure of the transducer.

In this study capacitive and resonant silicon sensor pressure transmitters were calibrated at different static pressures and the performance curves were compared. All measurement devices were traced to national standards through the Brazilian Calibration Network.

Measuring small pressure differentials at nearly atmospheric pressure can be easily and very accurately made with micromanometers or other similar equipments. However, the same is not true at high pressures. Sometimes, two dead weight testers are used to measure the pressure at each port of the transmitter, thus resulting in a reliable pressure differential measurement. In this research, as an alternative procedure, it was decided to use a pressure amplifier at each port of the transmitter, from nearly atmospheric pressure up to the operating pressure of the transmitter. Thus, if the pressure amplification factor is known accurately, the high pressure at each port of the transmitter can be calculated very accurately from the measured low pressure , and, thus, the pressure differential.

The objective of this paper is to determine the influence of the operating static pressure of the transmitter on its performance curve. First of all, a device is constructed to amplify the pressure from a nearly atmospheric value up to the operating one at each transmitter port. The amplification factor and its uncertainty are thus estimated, and used to calculate the transmitter pressure differential from the measured one at nearly atmospheric value. A statistical analysis is then used to demonstrate that the reduction in the indicated transmitter pressure differential, when the static pressure increases, is due to its performance dependence on the transmitter operating pressure, which must be taken into account during its calibration.

2. PRESSURE TRANSMITTERS

A SMAR capacitive transmitter, model LD301, with basic accuracy of ± 0,04 % of the measured pressure differential, and a YOKOGAWA resonant silicon transmitter, model EJX 110A, with basic accuracy of ± 0,04 % were used in the calibration.

For measuring low pressures, before amplification, an ASHCROFT AQS-2-CI transmitter was used with a basic accuracy of ± 0,0003 kgf/cm² (0,00003 MPa). For measuring high pressures, a DRESSER AQS-2 transmitter was used with a basic accuracy of ± 0,036 kgf/cm² (0,0035 MPa).

3. THE PRESSURE AMPLIFIER EQUIPMENT

Each of the two basic units consists of two axially coupled circular pistons of different diameters, connecting the low pressure (nearly atmospheric) side of the equipment to its high pressure side, where each transmitter port is attached to. Each unit can be displaced inside a two axially coupled cylinders with slightly larger diameters, thus varying each chamber volume, and, therefore, its pressure.

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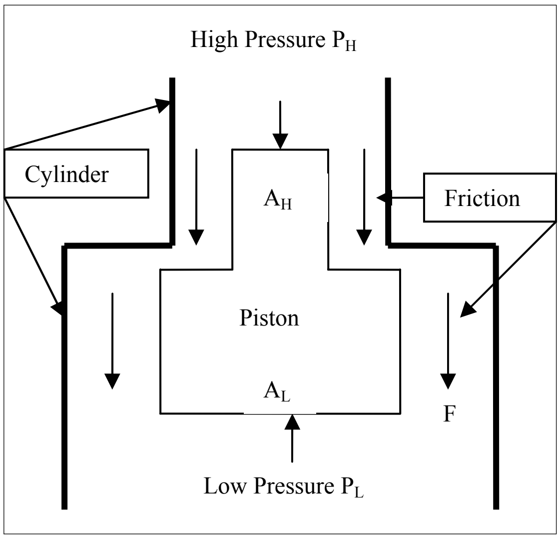

Fig. 1 . Basic Unit Schematic

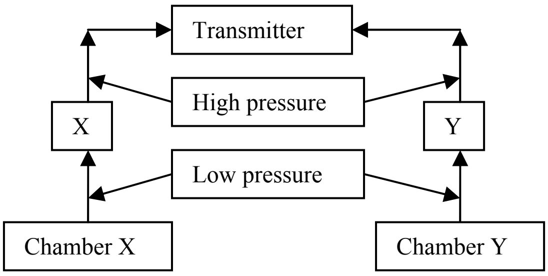

Fig. 2 . Schematic of the equipment, X and Y basic units.

Fig. 1 shows the basic unit schematic, where the piston is being displaced upwards. Under steady state conditions, there is an equilibrium of forces, as indicated by (1).

$$P_H.A_H = - F + P_L.A_L - m.g \qquad (1)$$

where *m* is the piston mass and *g* is the gravity. If the piston velocity is constant, there is clearly a linear relationship between low and high pressure values. When the piston is displaced horizontally, the piston mass term can be neglected. The friction term *F* can be minimized by stopping the system and optimizing the clearance gap between piston and cylinder. Furthermore, it is a well known fact in the dead weight tester technology that the friction force can be reduced by rotating the piston, so that the relationship between high and low pressures approaches a value that is inversely proportional to the piston area relationship A_b/A_a, which for this equipment was designed to be 100 :1.

Due to design difficulties it was decided not to optimize the friction and to experimentally determine a linear relationship between high and low pressures, (1), by measuring the pressure at the high pressure side of the piston at different measured low pressures for each basic unit called, respectively, X and Y, Fig. 2. A straight line, (2), was fitted to the measured curve P_H (high pressure) as a function of P_L (low pressure), both expressed in kgf/cm² (1 kgf/cm² = 0,0980665 MPa), as shown in Fig. 3 and 4.

$$P_H = a + b.P_L \qquad (2)$$

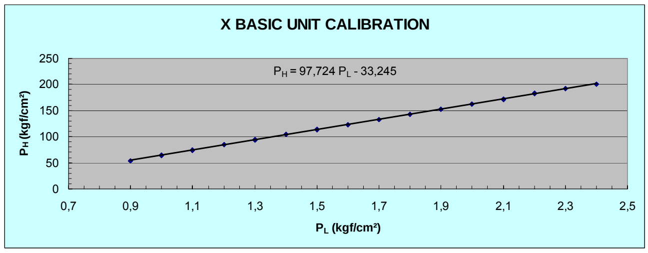

Fig. 3 . X basic unit calibration (1 kgf/cm² = 0,0980665 MPa)

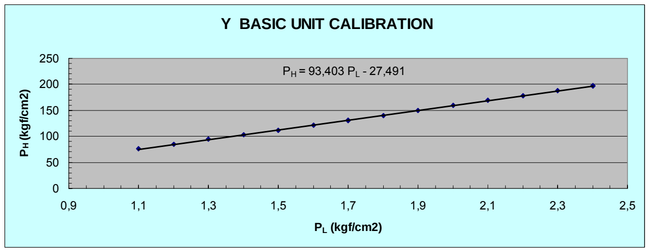

Fig. 4 . Y basic unit calibration (1 kgf/cm² = 0,0980665 MPa)

It can be seen that the straight line does not cross the axis at zero because of friction and piston weight. Actually, a further development will determine the adequate clearance between piston and cylinder in order to prevent leakage and reduce friction, which is responsible for the large transient times required for the equipment to achieve equilibrium.

In order to reduce the uncertainty of estimating the pressure at the transmitter port (high pressure side) from the measured low pressure, several measurements had to be made. The uncertainty of the coefficients a an b can be estimated by assuming that they are a function of the measured values $P_{H,i}$ and $P_{L,i}$, for i = 1 to n, through the least square fit relationships (3) and (4), according to[1] and [2].

$$a = \frac{\sum_{i=1}^{n} P_{H,i} \cdot \sum_{i=1}^{n} P_{L,i}^2 - \sum_{i=1}^{n} P_{L,i} \cdot \sum_{i=1}^{n} P_{H,i} . P_{L,i}}{n.\sum_{i=1}^{n} P_{L,i}^2 - \left(\sum_{i=1}^{n} P_{L,i} \right)^2} \qquad (3)$$

$$b = \frac{n.\sum_{i=1}^{n} P_{H,i} . P_{L,i} - \sum_{i=1}^{n} P_{H,i} . \sum_{i=1}^{n} P_{L,i}}{n.\sum_{i=1}^{n} P_{L,i}^2 - \left(\sum_{i=1}^{n} P_{L,i} \right)^2} \qquad (4)$$

The combined uncertainty [3] of a (u_a) and b (u_b) can be calculated, in (5) and (6), from the high pressure measurement standard uncertainties u_H and low pressure measurement standard uncertainty u_L calculated with a coverage factor equal to 2.

$$u_a^2 = \sum_{j=1}^{n}\left(\frac{\partial a}{\partial P_{H,j}}.u_H\right)^2 + \sum_{j=1}^{n}\left(\frac{\partial a}{\partial P_{L,j}}.u_L\right)^2 \quad (5)$$

$$u_b^2 = \sum_{j=1}^{n}\left(\frac{\partial b}{\partial P_{H,j}}.u_H\right)^2 + \sum_{j=1}^{n}\left(\frac{\partial b}{\partial P_{L,j}}.u_L\right)^2 \quad (6)$$

The partial derivatives in (5) and (6), known as sensitivity coefficients, can be calculated by differentiating (3) and (4), either algebraically, or using available softwares in the market for obtaining the required expressions. In this research, the derivatives were numerically calculated, resulting in a less troublesome procedure. The expanded uncertainties (95,45 % confidence level) [3], U_a and U_b, can be calculated multiplying the standard uncertainties u_a and u_b by Student-t value. Tables 1 and 2 present the values of the parameters used for calculating the uncertainties.

Table 1 . Uncertainty calculation for X basic unit

Parameter	Unit	a	b
Value		-33,245	97,724
U_H	kgf/cm²	0,036	0,036
U_L	kgf/cm²	0,0003	0,0003
u		0,0151	0,0088
n		32	32
t (2.n)		2,0435	2,0435
U	kgf/cm²	0,031	0,018

a = (-33,245 ± 0,031) kgf/cm² (7)

b = (97,724 ± 0,018) (8)

Table 2 . Uncertainty calculation for Y basic unit

Parameter	Unit	a	b
Value		-27,491	93,403
U_H	kgf/cm²	0,036	0,036
U_L	kgf/cm²	0,0003	0,0003
u		0,019	0,011
n		28	28
t (2.n)		2,0475	2,0475
U	kgf/cm²	0,039	0,022

a = (-27,491 ± 0,039) kgf/cm² (9)

b = (93,403 ± 0,022) (10)

The standard deviation of the fitting, (2), was 0,553 kgf/cm² for X basic unit, and 0,533 kgf/cm² for Y basic unit. A reduced standard deviation of the fitting can be obtained when the time required for data taking increases, thus reducing the scatter. However, the uncertainties of the coefficients are smaller because many measurements were taken. When calibrating the pressure transmitter it was decided to wait a much longer time until the equilibrium is set up, as demonstrated by the small value of the achieved standard deviation.

4. PRESSURE TRANSMITTER CALIBRATION

The calibration of the pressure transmitters can be done by placing X and Y basic units, respectively, between each low pressure chamber, where the pressure P_L can be set up, and each transmitter port, where the pressure is P_H , as shown in Fig. 2.

In low pressure chambers X and Y the pressure P_L is measured by the ASHCROFT AQS-2-CI transmitter. The amplified pressure P_H is calculated by (2). Its standard uncertainty u_H is calculated by (11), following [3].

$$u_H^2 = u_a^2 + \left(P_L.u_b\right)^2 + \left(b.u_L\right)^2 \quad (11)$$

The estimated true pressure differential ΔP_{true} at the transmitter ports can be calculated as the difference between the amplified pressures by X and Y basic units.

$$\Delta P_{true} = \left(P_H\right)_X - \left(P_H\right)_Y \quad (12)$$

The estimated standard uncertainty of the true pressure differential u_{true} is calculated by (13), using (11).

$$u_{true}^2 = \left(u_H\right)_X^2 + \left(u_H\right)_Y^2 \quad (13)$$

The indicated pressure differential by the pressure transmitter ΔP_{trans} is then compared to its true value ΔP_{true} , for different static pressures.

The calibration was performed by setting a static pressure value at the Y port of the transmitter, and then varying the static pressure at the X port in order to get the following pressure differentials : 1,0, 1,2, 1,4, 1,6, 1,8, 2,0, 2,2 and 2,4 kgf/cm². The procedure was repeated for the following static pressures : atmospheric, 100, 120, 140, 160, 180 and 200 kgf/cm². The calibration was very time consuming in order to allow sufficient time for the equilibrium to be achieved.

4.1 Calibration of SMAR LD301 transmitter

Table 3 shows the indicated pressure differential by the transmitter ΔP_{trans} , for several values of the true pressure differential ΔP_{true} and different static pressures. Fig. 5 shows graphically the results.

Table 3 . Indicated pressure differential ΔP_{trans} of SMAR LD301 transmitter.

ΔP_{trans} - INDICATED PRESSURE DIFFERENTIAL BY THE TRANSMITTER (kgf/cm²)							
$(\Delta P)_{true}$	$(P_H)_Y$ - STATIC PRESSURE (kgf/cm²)						
kgf/cm²	0,0	100,0	120,0	140,0	160,0	180,0	200,0
1,000	0,997	0,984	0,979	0,976	0,973	0,965	0,960
1,200	1,202	1,179	1,174	1,168	1,172	1,163	1,154
1,400	1,402	1,380	1,374	1,366	1,365	1,350	1,345
1,600	1,598	1,573	1,571	1,564	1,556	1,550	1,533
1,800	1,803	1,766	1,765	1,751	1,753	1,737	1,726
2,000	1,997	1,964	1,959	1,947	1,944	1,927	1,919
2,200	2,203	2,163	2,152	2,148	2,144	2,129	2,113
2,400	2,403	2,353	2,356	2,337	2,341	2,319	2,301

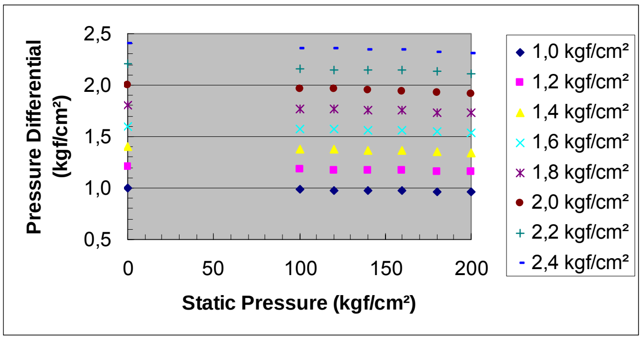

Fig. 5 . Indicated pressure differential ΔP_{trans} of SMAR LD301 transmitter.

It can be clearly seen that when the static pressure increases, there is a trend towards the reduction of the indicated pressure differential by the transmitter.

In order to check the statistical significance of the results, the data were fitted by a straight line (14).

$$\Delta P_{trans} = a + b.\Delta P_{true} \qquad (14)$$

Table 4 shows the calculated values of a, b, s, U_a, U_b and U_{true} , according to (3), (4), (5), (6), (11), (12) and (13).

Table 4 . Statistical analysis of the SMAR LD301 transmitter calibration

$(P_H)_Y$	a	b	s	U_a	U_b	U_{true}
kgf/cm²	kgf/cm²		kgf/cm²	kgf/cm²	kgf/cm²	kgf/cm²
0,0	-0,0036	1,0025	0,0025	0,0014	0,0008	0,0003
100,0	0,0059	0,9790	0,0023	0,0990	0,0564	0,075
120,0	-0,0012	0,9808	0,0027	0,1035	0,0589	0,078
140,0	0,0020	0,9736	0,0029	0,1074	0,0612	0,082
160,0	-0,0005	0,9744	0,0026	0,1126	0,0641	0,085
180,0	0,0006	0,9658	0,0034	0,1169	0,0665	0,090
200,0	0,0025	0,9582	0,0017	0,1214	0,0691	0,094

Table 4 shows that the standard deviation s is small, demonstrating that the data scatter is small and thus qualifying the experimental procedure. It can also be shown that the angular coefficient of the straight line decreases with the static pressure, indicating that the transmitter reads smaller values of the pressure differential.

Considering that the statistical distribution of the angular coefficient of the fit is normal, with an average value *b* and standard deviation u_b $(=U_b/2)$, as shown in Table 4 for different static pressures, a variable (x_i) can be defined in (15) as the difference between its value at atmospheric pressure (b_{oi}) and at a given static pressure (b), with the average value given in (16). According to [3], the standard deviation (u_x) is given by (17).

$$x_i = b_{oi} - b_i \qquad (15)$$

$$\bar{x} = b_o - b \qquad (16)$$

$$u_x^2 = u_{bo}^2 + u_b^2 \qquad (17)$$

The statistical significance of the results can be evaluated by calculating the probability that the variable x_i be inside the range (18)

$$\bar{x} - |\bar{x}| \le x_i \le \bar{x} + |\bar{x}| \qquad (18)$$

Table 5 . Statistical significance of results

$(P_H)_Y$	$\bar{x}$	u_x	η	P(-η,η)
kgf/cm²	kgf/cm²	kgf/cm²		%
100,0	0,0234	0,0282	0,8310	59,4
120,0	0,0216	0,0295	0,7343	53,7
140,0	0,0288	0,0306	0,9430	65,4
160,0	0,0281	0,0320	0,8759	61,9
180,0	0,0366	0,0333	1,1013	72,9
200,0	0,0443	0,0346	1,2818	80,0

It can be seen from Table 5 that the probability P(-η,η) of (18) to be satisfied is higher for large values of the static pressure, where $\eta = (\bar{x} - 0)/u_x$. In the limit, when the probability approaches 100 %, the two distributions do not overlap, meaning that the two calibration curves are different, and that the transmitter performance varies with static pressure. It is usual to adopt a probability value of 95,45 % (approximately 5 % significance level) as a lower limit for accepting that the events are independent.

In order to conclude definitely that the transmitter performance curve varies with static pressure, the system must be redesigned to reduced the uncertainty value u_{true} and thus u_b . By examining the results of this research one can only say that there is a trend for the transmitter to indicate lower values of the differential pressure when the static pressure increases.

4.2 Calibration of YOKOGAWA EJX 110A transmitter

The same developed experimental procedure was used to produce de following results.

Table 6 . Indicated pressure differential ΔP_{trans} of YOKOGAWA EJX 110A transmitter.

ΔP_{trans} - INDICATED PRESSURE DIFFERENTIAL BY THE TRANSMITTER (kgf/cm²)							
$(\Delta P)_{true}$	$(P_H)_Y$ - STATIC PRESSURE (kgf/cm²)						
kgf/cm²	0,0	100,0	120,0	140,0	160,0	180,0	200,0
1,000	1,001	0,985	0,983	0,980	0,975	0,970	0,968
1,200	1,201	1,180	1,182	1,175	1,168	1,161	1,154
1,400	1,401	1,390	1,385	1,375	1,367	1,356	1,350
1,600	1,601	1,575	1,584	1,565	1,564	1,550	1,539
1,800	1,801	1,770	1,775	1,759	1,751	1,744	1,739
2,000	2,001	1,970	1,968	1,963	1,947	1,934	1,927
2,200	2,201	2,169	2,165	2,150	2,144	2,134	2,123
2,400	2,401	2,376	2,364	2,353	2,335	2,319	2,310

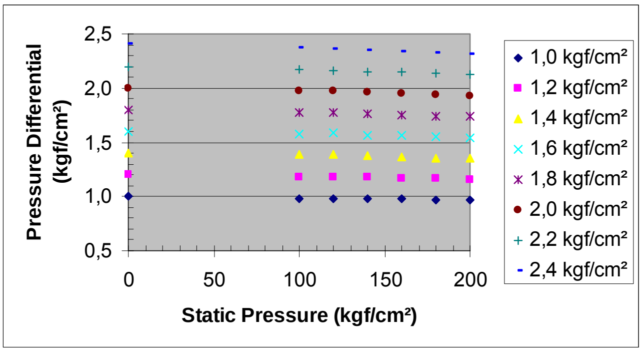

Fig. 6 . Indicated pressure differential ΔP_{trans} of

YOKOGAWA EJX 110A transmitter.

Table 7 . Statistical analysis of the YOKOGAWA EJX 110A transmitter calibration

$(P_H)_Y$	a	b	s	U_a	U_b	U_{true}
kgf/cm²	kgf/cm²		kgf/cm²	kgf/cm²	kgf/cm²	kgf/cm²
0,0	0,0008	1,0001	0,0004	0,0008	0,0005	0,0003
100,0	-0,0046	0,9891	0,0055	0,1001	0,0569	0,075
120,0	0,0039	0,9835	0,0038	0,1038	0,0591	0,078
140,0	0,0010	0,9788	0,0034	0,1079	0,0614	0,082
160,0	0,0042	0,9718	0,0026	0,1121	0,0638	0,085
180,0	0,0031	0,9664	0,0025	0,1167	0,0665	0,089
200,0	0,0025	0,9625	0,0030	0,1218	0,0693	0,094

The same conclusions can be obtained from Table 8. In order to conclude definitely that the transmitter performance curve varies with static pressure, the system must be redesigned to reduced the uncertainty value u_{true} and thus u_b . By examining the results of this research one can only say that there is a trend for the transmitter to indicate lower values of the differential pressure when the static pressure increases, although less than SMAR transmitter.

Table 8 . Statistical significance of results.

$(P_H)_Y$	$\overline{X}$	u_x	η	P(-η,η)
kgf/cm²	kgf/cm²	kgf/cm²		%
100,0	0,0110	0,0285	0,3851	30,0
120,0	0,0166	0,0295	0,5628	42,6
140,0	0,0213	0,0307	0,6921	51,1
160,0	0,0282	0,0319	0,8843	62,3
180,0	0,0336	0,0332	1,0123	68,9
200,0	0,0376	0,0347	1,0839	72,2

5. CONCLUSIONS

A device has been designed and constructed to amplify the static pressure from a nearly atmospheric value up to a large one, so that a differential pressure transmitter can be calibrated at the operating pressure. A methodology was developed to metrologically characterize the transmitter, including the uncertainty of calculating the amplified pressure from the measured low pressure value. The device has to be redesigned to decrease the effect of friction in the clearance between piston and cylinder, reduce the time required to achieve the equilibrium conditions and reduce the uncertainty of calibrating a differential pressure transmitter at the operating pressure. To partially compensate for this difficulty a large number of data points was used.

A methodology was then developed to calibrate two different differential pressure transmitters at the operating pressure. It was shown that there is a definite trend for the transmitters to indicate a smaller value when the static pressure increases. However, a statistical analysis was used to show that a clear evidence of the static pressure influence on the transmitter performance curve can only be obtained when the device is redesigned and the uncertainty of estimating the true differential pressure is reduced. The used statistical method is able to compare the performance of two different operating principle transmitters.

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